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HANDBOOK FOR THE IMPLEMENTATION OF THE DESIGN TO COST CONCEPT

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FINAL REPORT

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FOREWORD

This handbook provides detailed instructions (together with illustrative numerical examples) for implementing various methodologies designed to provide a Program Manager with analytical tools for solving various problems encountered during system development. The management tools are applicable to nearly any system ranging from a simple combination of a few subsystems to a complex aircraft. Briefly stated, these tools allow for continuous and systematic evaluation of overall system reliability, optimal allocation of resources in system reliability improvement programs, and optimal allocation of resources in system effectiveness improvement programs.

The first two sections of the handbook are intended to show the potential of the methodology to the Program Director. The following sections describe the models and the step-by-step procedures for their use so that program personnel can understand the mechanics and apply the methodology to their particular program. Rather than develop rigorous mathematical proof for the models, numerical examples were used to show how to implement the methodology. The examples also indicate that input data are available using engineering estimates and historical results of "like" subsystems in the conceptual phase. Then, as test results become available in the validation and full scale development phases the data base is continuously improved.

The authors wish to give special acknowledgment to William H. Newhart, Jr. (Lt Col, USAF Ret.) who was instrumental in developing the basic architecture of the methodology, applied the methodology to the Grasshopper Mine Program, and after retirement from the USAF made many substantial contributions during the preparation of the handbook. The authors also wish to acknowledge Col James L. McKenna for his support and encouragement in applying the methodology to the on-going EF-111A program.

The views presented in this report are those of the authors and do not necessarily reflect the policy or position of the Air Force or The Department of Defense. This report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents various models and methodologies in the form of a practical handbook of management tools. These management tools provide a system Program Manager with the means to do the following on a day-by-day basis: (1) Evaluate current system progress; (2) Identify problem areas associated with various subsystems where corrective actions or additional subsystem options are required; (3) Identify subsystems for which a reduction in performance has a small effect on total system performance and investigate if these subsystems can be replaced by lower cost subsystems with the cost savings invested more effectively in the

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) improvement of other more critical subsystems; (4) Select the combination of subsystem options yielding the maximum total system performance achievable at the Design to Cost goal, i.e., optimal allocation of resources; and (5) Evaluate the effect of any proposed change in system design and its impact on Design to Cost goals. The above objectives can be accomplished with the aid of the following mathematical models: Mission Completion Success Probability (MCSP), Designing to System Performance/Cost (DSPC), and Designing to System Performance/Cost/Effectiveness (DSPCE). The MCSP model provides a measure of total system reliability in terms of mission completion. It also identifies the mission critical subsystems and performs a sensitivity analysis which measures the impact of subsystem reliability improvement on total system performance. The DSPC model provides for optimal allocation of resources whenever reliability improvement programs are undertaken. The DSPC methodology determines the maximum performance achievable (by selection of the optimal combination of subsystem options) at the associated cost. Certain subsystems directly influence the measure of effectiveness of the system. If options (in the form of varying levels of effectiveness and the cost associated with each level) are available for these subsystems, then the DSPCE methodology can be implemented to determine that combination of subsystem options yielding the maximum system effectiveness at any prescribed cost. This handbook contains detailed instructions showing how to implement each model, discussions of model outputs, and appropriate examples.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I

INTRODUCTION

A. GENERAL

In June of 1973, Deputy Secretary of Defense William P. Clements, Jr. issued a memorandum to the secretaries of the military departments and the Defense Systems Acquisition Review Council (DSARC) to establish Design to Cost (DTC) goals for major defense system programs. This memorandum began a major first step in DTC implementation. The DTC concept is defined as "the establishment of cost goals early in the development process and the management and control of future acquisition, operating and support costs to these goals by the conduct of practical tradeoffs between system capabilities, cost, and schedule." Although the DOD DTC concept is quite clear, it does not provide specific guidance in establishing techniques for implementing DOD DTC policies. This handbook presents an approach for translating some of the DOD DTC policies into effective management tools. These management tools address the tradeoffs between system capability and cost but do not consider tradeoffs involving schedule. Furthermore, to place this methodology in proper context, it is necessary to discuss system capability in terms of performance levels related to mission requirements. For any system there are certain performance specifications, e.g., speed, range, accuracy, etc., which must be met. After these specifications have been met, how well a system performs its mission is strictly a function of its inherent reliability and effectiveness. Therefore, in this handbook, the system capability tradeoffs are in terms of performance and effectiveness where performance is measured by mission reliability.

The management of any system program is a continuous, iterative process. Throughout the system development, design changes in various subsystems are proposed while the accuracy of cost estimates as well as reliability estimates are being improved. To effectively manage a program and meet DTC goals, it is necessary that the Program Manager have a timely feedback of current cost and performance estimates of all proposed subsystem options. On a day-by-day basis, the Program Manager should have the means to:

- Evaluate current progress of system development.

- Identify problem areas associated with various subsystems where corrective actions or additional subsystem options are required.

- Identify subsystems whose performance levels are more than adequate to meet mission requirements and investigate if these subsystems can be replaced by lower cost subsystems (which generally implies lower performance) with the cost savings invested more effectively in the improvement of other more critical subsystems, i.e., optimal allocation of resources.

- Select the combination of subsystem options yielding the maximum total system performance achievable at the DTC goal.

- Evaluate the effect of any proposed change in system design and its impact on DTC goals.

The management tools described in this handbook furnish a Program Manager with a simple means to address these objectives by providing a systematic and standardized procedure for basing his day-by-day decisions on the most recent data base as it is continuously being updated during system development.

B. BACKGROUND

During the past three years, the Directorate of Aerospace Studies, AFSC, (formerly designated the Office of the Assistant for Study Support) has been engaged in a variety of studies concerning test and evaluation and the development of program management tools relating to Design to Cost, and Life Cycle Cost. In the first of these studies the test and evaluation program for the A-7D was analyzed (Reference 1). In the A-7D analysis, the impact of reliability on logistic support costs was treated very briefly, and in subsequent work these ideas were extended leading to the development of a generalized methodology. A description of the methodology is presented in the form of an annotated briefing in Reference 2, and Reference 3 contains a detailed mathematical development together with some illustrative aircraft oriented examples. However, the methodology is not restricted to aircraft; it is general enough to be applied to nearly any system. Recent efforts have been devoted to applications of the methodology to specific programs. Reference 4 contains the results of such an application to a target activated munitions program (Grasshopper Mine), and portions of the methodology have been applied to the Jamming Subsystem of the EF-111A and are documented in Reference 5.

In the belief that the models might be of use to the program managers, program engineers, and system designers of a large variety of systems, this handbook is presented to explain in detail how to apply the methodology without burdening the user with the detailed mathematical development contained in Reference 3. It should be emphasized, however, that this methodology cannot replace judgement and the expertise in the specialized disciplines associated with a program office. Rather, these are management tools which can be used by the Program Manager to integrate the inputs of the various disciplines thereby maintaining a continuing, comprehensive picture of program status.

An overview of the methodology is presented in Section II. The remaining sections provide detailed guidance for implementing the models.

SECTION II

OVERVIEW

A. GENERAL

A brief description of the models is presented in this section to acquaint the program manager with the general methodology and indicate the potential use as a management tool. In the subsequent sections, detailed instructions showing how to implement each model will be presented together with discussions of model outputs, and appropriate examples.

B. MISSION COMPLETION SUCCESS PROBABILITY

The first model to be considered is the Mission Completion Success Probability (MCSP) model. The MCSP model determines the probability that a system completes its mission without being degraded below acceptable limits because of a critical failure of one or more of its subsystems. Therefore, assuming that all other technical specifications such as speed, range and accuracy have been met, the MCSP is a measure of total system performance. The principal use of MCSP models is to provide early insight into the operational impact of system reliability. MCSP models also call attention to reliability problem areas early in the program so that appropriate action can be taken.

Figure 1 shows the Input-Output Diagram for the MCSP Model. The inputs required for implementing the MCSP model are further described as follows:

- Mission Profile - The mission profile is a detailed description of the operational tasks or mission the system is expected to perform. The mission is divided into phases and during each phase certain functions must be performed by various subsystems. For example, the profile for a tactical fighter aircraft performing an interdiction mission might consist of the following phases: Start, ground operation and takeoff, penetration to target, target area, return to base, landing and ground operation.

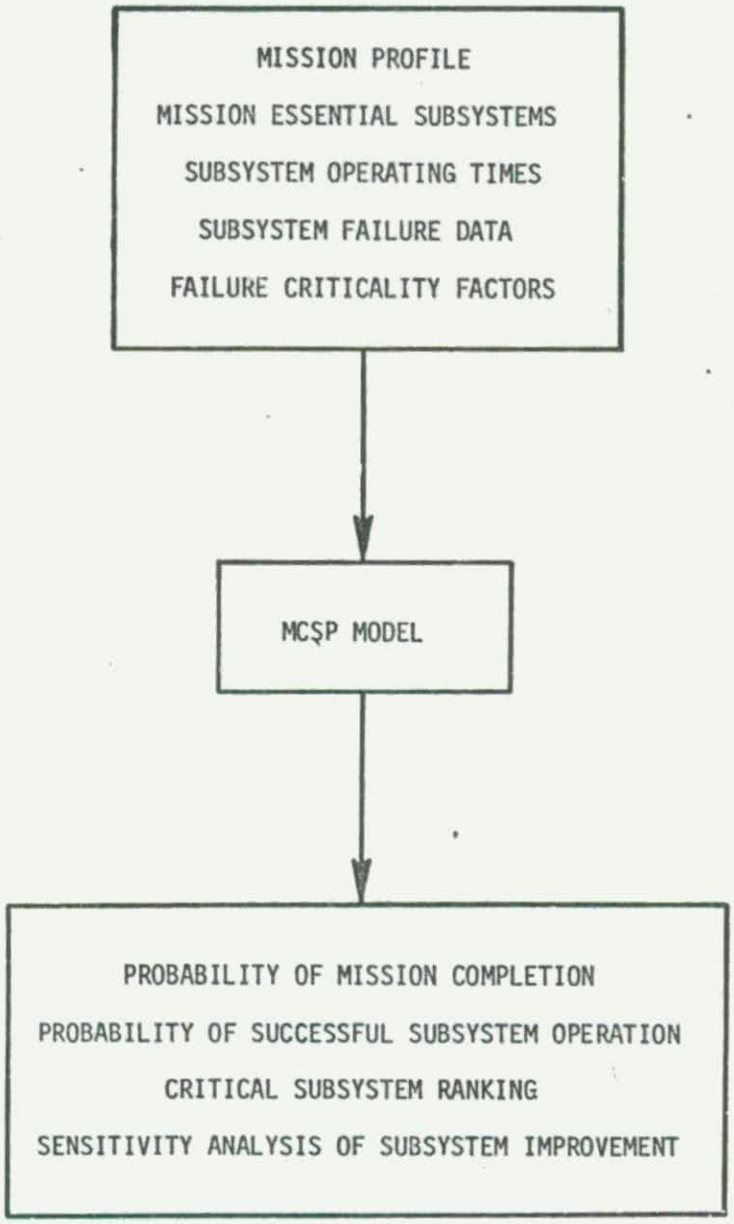


Figure 1. Input-Output Diagram of the Mission Completion Success Probability Model.

• **Mission Essential Subsystems** - A particular mission requires that certain operational functions be performed for the system to successfully complete its mission, e.g., communications, navigation, target accuisition, etc. Those subsystems required to perform these functions are defined as the mission essential subsystems. Mission essential subsystems can be considered a generic term for dividing the total system into functional units. Depending on the application, these functional units could be subsystems, line replaceable units, or a similar breakdown as appropriate. The term mission essential subsystems will be used throughout this handbook to designate the subunits of the total system.

• Subsystem Operating Times - In conjunction with the phases defined in the mission profile, the mission essential subsystem operating times (duty cycles) for each phase are determined, or in the event a subsystem performs only a single operation, the phase in which that operation occurs is specified. For example, the landing gear of an aircraft would be required during ground operation, takeoff and landing. Thus, the landing gear duty cycle would correspond to these phases of the mission profile.

• Subsystem Failure Data - If the mission essential subsystem is to operate over a period of time, the failure data is usually in the form of mean time between failure (MTBF). For single event subsystems, the failure data is usually in the form of the ratio of the number of failures to the number of trials of the event.

• Failure Criticality Factors - Although all failures require some type of maintenance action, all failures do not necessarily degrade the system's capability to perform the required mission. For example, a burned out bulb is normally not as serious as a burned out transistor in a critical circuit. Thus, a measure of the seriousness of the failure is required. This measure is provided by the failure criticality factor, which is the fraction of the total number of failures that a mission essential subsystem would be expected to experience during the mission which are serious enough to unacceptably degrade or abort the mission. In mathematical terms, the failure criticality factor is the conditional probability of unacceptable degradation given that the subsystem experiences a failure during the mission.

With the above inputs, the MCSP model outputs are:

- System MCSP - The probability that all mission essential subsystems successfully perform their functions throughout all mission phases. This is the primary output of the MCSP model and provides a measure of system reliability with respect to the defined mission.

- Probability of Successful Subsystem Operation - The probability that a particular mission essential subsystem successfully performs its function can be examined for a particular mission phase or for any number of consecutive phases.

- Critical Subsystem Ranking - The model ranks the mission essential subsystem in terms of the probability of experiencing a critical failure during the mission. This identifies those subsystems with the greatest likelihood of degrading the system below acceptable limits during the mission.

- Sensitivity Analysis - The model provides a sensitivity analysis which shows the increase in system MCSP resulting from reliability improvement of one or more mission essential subsystems.

In addition to illustrating the operational impact of system and subsystem reliability, the MCSP methodology may be useful in establishing realistic reliability goals. For instance, the sensitivity analysis shows that reliability improvement of the subsystems beyond certain values has essentially no impact on MCSP enhancement. On the other hand, if the MCSP is relatively insensitive to any reliability improvement of a particular subsystem this gives an indication that perhaps a lower cost, less reliable subsystem could be substituted, with the resulting cost savings more effectively invested in improving reliability of other subsystems. The MCSP model also plays a very important role in the Designing to System Performance/Cost model, which is described in the next section. The inputs and outputs of the MCSP model are described in greater detail in Section III. Also, Section III contains numerical examples to aid the reader in understanding the methodology.

C. DESIGNING TO SYSTEM PERFORMANCE/COST

The second model to be considered is the Designing to System Performance/Cost (DSPC) model. This model provides for the optimal allocation of resources and can be employed during preliminary design to select the initial or Baseline System configuration from among competing subsystems. However, its main application is during the development process if additional subsystem options become available or a reliability improvement program is undertaken.

Once the Baseline System has been established, the MCSP model can be applied to: determine if the reliability requirements are adequate; identify the mission critical subsystems; and to perform a sensitivity analysis which shows the impact on mission success due to reliability improvements of individual subsystems or groups of subsystems. Often, the Baseline System MCSP falls below a level deemed necessary to meet mission requirements. When this happens, mission requirements can either be relaxed, or it is necessary for the Program Manager to initiate a reliability improvement program. A great deal of time, effort, and money can be wasted if such a program is not conducted in a systematic manner, e.g., the reliability of some subsystems might be improved more than necessary, while the reliability of other subsystems might not be improved enough. The DSPC methodology provides a means of conducting a reliability improvement program in a systematic manner. This is accomplished by investigating reliability improvement options. These options, in the form of varying levels of subsystem reliability and the cost associated with each level, would involve established techniques for improving reliability and generally could range all the way from replacing low reliability components with higher reliability components to complete redesign of the subsystem. (Even if the Baseline System MCSP appears satisfactory, the Program Manager should consider additional subsystem options since in any case the developing command, using command, and supporting command are all vitally interested in the most reliable system that the available funding can provide.)

During the development of a system, the Program Manager is continually tasked to evaluate engineering changes or modifications which improve performance, reduce costs, or both. It can be a formidable task to determine which combination of options yields the maximum MCSP at some prescribed level of cost. The DSPC model provides a simple algorithm for calculating the optimal MCSP versus cost curve and identifies the combination of subsystem options associated with each vertex point on the curve. To demonstrate the necessity for such an efficient algorithm, consider an aircraft system such as the A-7D. For this aircraft, a total of 36 mission essential subsystems were identified. If for example, during the development phase, 2 reliability improvement options had been available for each subsystem, then the total number of possible system configurations (combinations of subsystem options) would have been:

$$3^{36} = 1.5 \times 10^{17} \quad .$$

Clearly, it would be impossible to investigate each of these combinations. Even if considerable initial screening could be accomplished and a very efficient digital computer were utilized to examine the combinations, the cost and time involved would be prohibitive. However, even in this extreme example and without any initial screening, the DSPC model would require at most 108 calculations in order to generate the optimal MCSP versus cost curve. Applying the DSPC methodology, the optimal MCSP versus cost curve can be determined quickly using an electronic calculator. A digital computer program is also available (Reference 3).

Figure 2 shows a typical output of the DSPC model. In this hypothetical example, the MCSP and cost of the Baseline System determine the starting point on the DSPC curve. The next point on the curve represents the best selection, among the available subsystem reliability improvement options, for a system configuration at the corresponding cost, i.e., for this particular cost there is no combination of subsystem options yielding a higher MCSP. Subsequent points on the DSPC curve are established in the same way and have the same interpretation. Thus, to each vertex point on the curve, there corresponds a uniquely defined combination of subsystem options, i.e., system configuration. These vertex points show the maximum performance achievable (by selection of the optimal combination of subsystem options) at the associated cost. Furthermore, all other combinations are nonoptimal and hence lie below the DSPC curve. This type of information can be of great value to the Program Manager as well as higher level Decision Makers since it provides an overall picture of achievable system performance as a function of cost. Such information could provide the basis for adjusting DTC goals or mission requirements. For example, with a fixed program cost, it may be more cost effective to purchase fewer systems (with higher MCSP) at a unit cost greater than originally planned. This was shown in application of the methodology to the Grasshopper Mine Program (Reference 4).

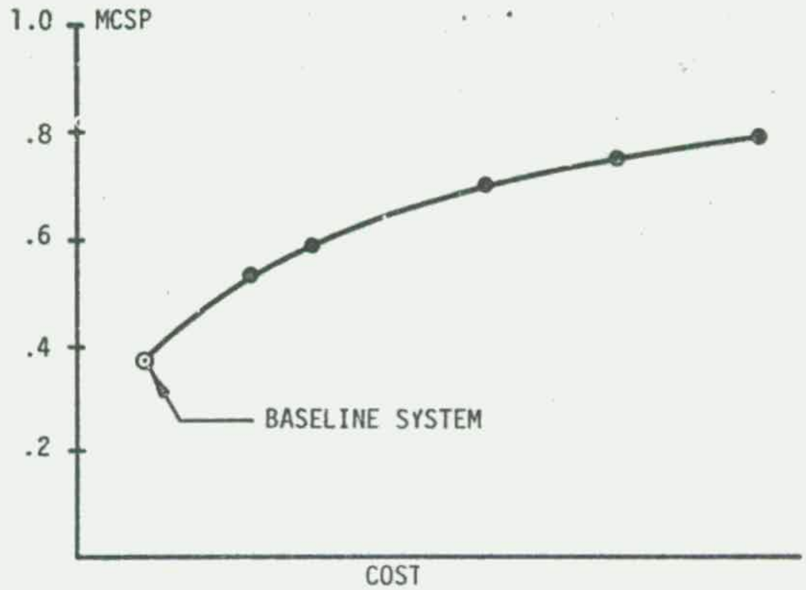


Figure 2. Typical Output of DSPC Model.

This type of analysis could also indicate where cheaper subsystems, which do not appreciably degrade performance, could be substituted for more expensive subsystems. The resulting savings could be invested in improving the subsystems having greater impact on mission success. It should also be noted that a designer of a subsystem can apply the same methodology in improving the subsystem reliability, i.e., selecting optimal component reliability options. In this case, the subsystem would play the role of the system and the subsystem components would play the role of the subsystems.

In Section IV, the DSPC model is explained in greater detail, and numerical examples are presented to facilitate understanding.

D. DESIGNING TO SYSTEM PERFORMANCE/COST/EFFECTIVENESS

The MCSP is a measure of the mission reliability of the total system; hence, it also plays a part in evaluating system effectiveness, e.g., an aircraft must reach its target, a land mine must be operative, etc. The DSPC model selects the optimal combination of subsystems to perform this aspect of the mission. However, the ultimate objective of the mission is at a higher level, e.g., to destroy a target, disable a tank, etc. This objective is used in the establishment of some measure of effectiveness for the total system. Certain subsystems more directly influence this measure of effectiveness than others, e.g., subsystems relating to weapons delivery accuracy, mine sensor range, etc. If options (in the form of varying levels of effectiveness and the cost associated with each level) are available for these subsystems, then the Designing to System Performance/Cost/Effectiveness (DSPCE) methodology can be employed to determine that combination of subsystem options yielding the maximum system effectiveness at any prescribed cost. Each effectiveness option will also be characterized by a certain level of reliability as well as effectiveness. For example, a highly sophisticated and accurate weapons delivery subsystem, with low reliability, might not be selected in an optimum system configuration because it leads to less mission effectiveness then a competing subsystem with lower accuracy but higher reliability. (If there are no effectiveness options available for those subsystems directly related to the measure of effectiveness, then only the DSPC model is applicable, i.e., the mission effectiveness associated with a particular system configuration determined to be optimum by the DSPC model will be the maximum effectiveness achievable at that particular cost).

Figure 3 depicts a typical output of the DSPCE model when subsystem effectiveness options are available. The discussion is similar to that presented for Figure 2 except that in this case the DSPCE algorithm optimizes total system effectiveness (which includes MCSP) with respect to cost. All other system configurations lead to points below the curve in Figure 3, (i.e., are non-optimal).

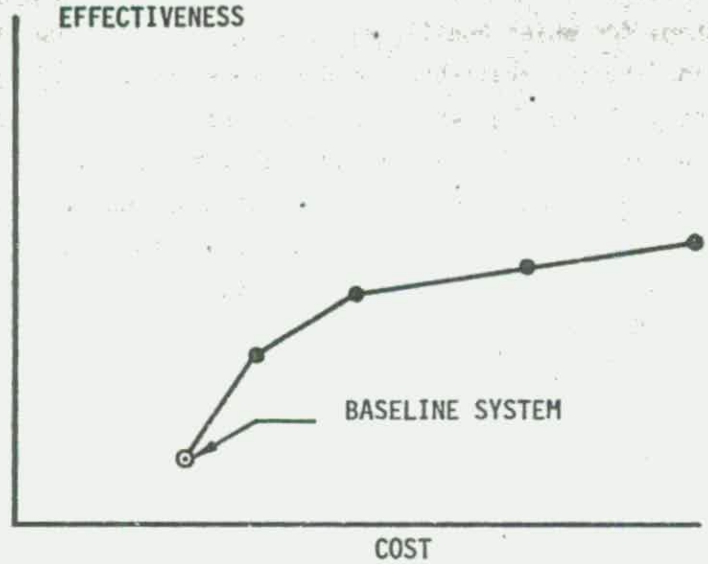


Figure 3. Typical Output of DSPCE Model.

The utility of the DSPCE algorithm is best illustrated by the results of the application of the methodology to the Grasshopper Mine Program (Reference 4). In this program, reliability options together with the warhead options led to 1,536 possible Grasshopper configurations. The application of the DSPCE methodology showed that only 7 of these configurations were optimal. The remaining 1,529 configurations led to lower effectiveness at their respective levels of cost and consequently were eliminated from consideration.

More details on the DSPCE methodology can be found in Section V along with a numerical example.

E. SYNOPSIS

Figure 4 presents a synopsis of the methodology in the form of an overview of the application of the DTC management tools described previously. Starting with the Baseline System configuration, which in some cases could have been established using DSPC techniques, the MCSP model determines the Baseline MCSP, ranks those subsystems with the greatest likelihood of causing degraded or aborted missions, and performs subsystem sensitivity analyses. This indicates to the Program Manager those subsystems for which additional options should be sought. When these additional options become available the DSPC model will identify the combination of options yielding the maximum MCSP (overall system reliability) at any prescribed level of cost. The DSPCE model analyzes effectiveness as well as reliability to identify the combination of subsystem options yielding the maximum mission effectiveness at any prescribed cost. If the system MCSP or effectiveness is marginal, or if the cost is too high, the program should be re-evaluated, and if possible, additional options should be obtained and the process repeated. This process can be applied early in the program using engineering estimates for input data. As the program continues, the data base is improved by incorporating test data. Thus, the Program Manager can make the best selection of subsystem options with respect to a constantly improving data base. The management tools described above are available, have been validated, and should be of interest to Program Managers and DOD Decision Makers in a wide variety of fields.

The discussions in this section have presented a brief description of the types of decision-making information that can be generated by the various methodologies that have been developed by the Directorate of Aerospace Studies. In the subsequent sections, step-by-step procedures for implementing the methodologies are presented.

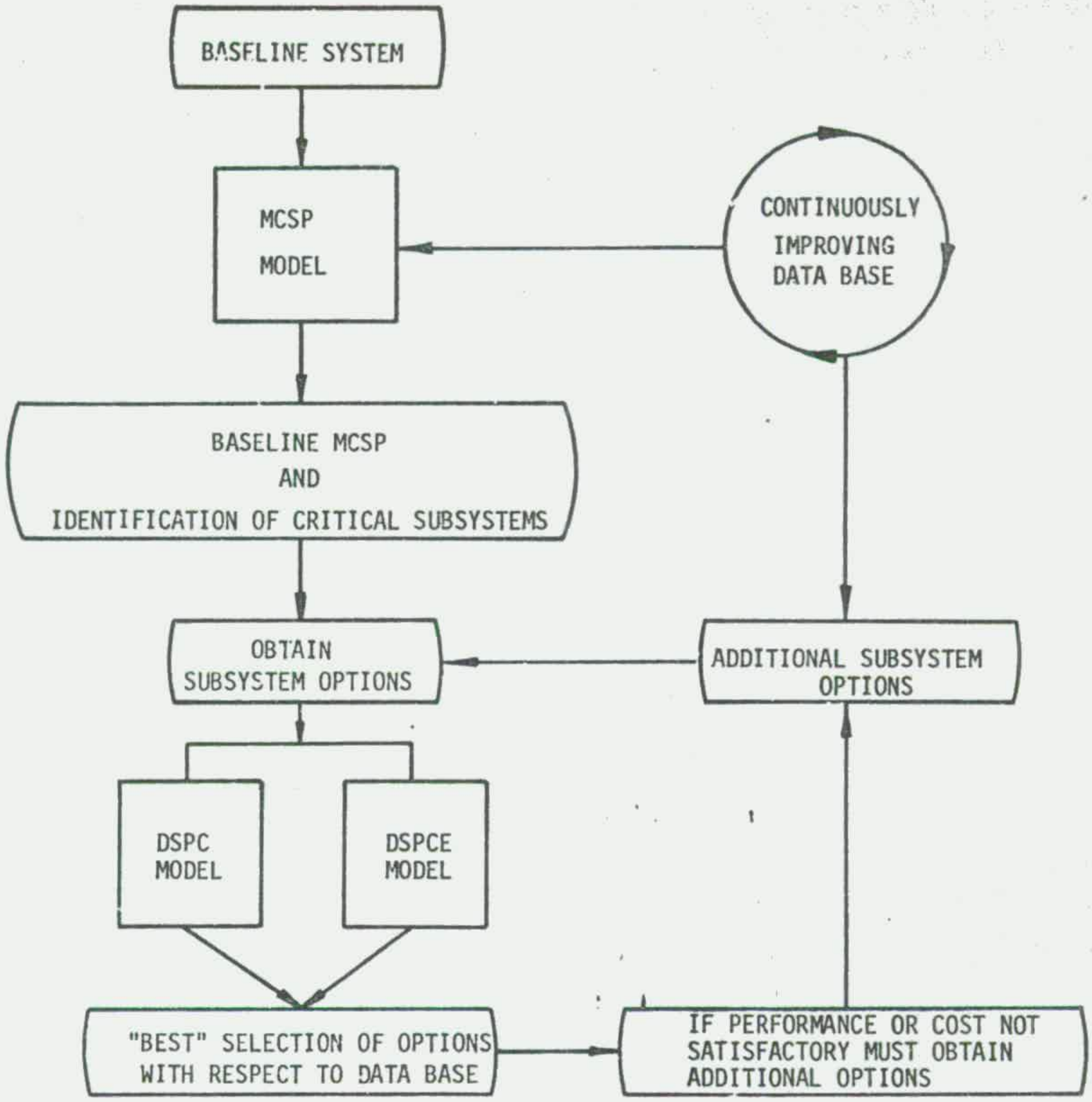


Figure 4. Synopsis of Methodology.

SECTION III

MISSION COMPLETION SUCCESS PROBABILITY MODEL

A. GENERAL

This and the remaining sections describe the procedures for implementing the models described in Section II. The methodology and instructions are written in general terms. However, each system has its own unique characteristics and the Program Manager, familiar with his own system, can easily adapt the general methodology to a comprehensive description of the performance of his specific system.

The Input-Output Diagram for the MCSP model was presented in Figure 1 on page10. The MCSP is a measure of the ability of a system to perform a proposed operational task for which it is being designed without being degraded below an acceptable level by a critical failure of any of its subsystems. In other words, it is a measure of the reliability of the total system in performing its proposed operational task. In this section each required input will be defined and discussed, and detailed instructions for calculating the outputs will be presented along with appropriate examples.

B. MCSP MODEL INPUTS

1. Mission Profile. The mission profile is a detailed description of a proposed operational task or mission the system is expected to perform. The Program Manager can translate the original system requirement into a mission profile which can be modified as the development cycle matures to best reflect the operational modes planned for the system. This places emphasis upon the importance of involvement of the user early in the development cycle and furnishes a rationale for the Program Manager to advocate constant communication across major command lines with the user. The mission is divided into phases, and during each phase certain functions must be performed if the system is to meet its operational requirements. If the system is required to perform several types of missions, then a mission profile can be defined for each mission. The MCSP model can then be applied to each of these individual missions. A mission

profile for target activated munitions is presented in Figure 5, page 32 and a mission profile for tactical interdiction is presented in Figure 7, page 37.

2. Mission Essential Subsystems. A particular mission profile identifies the operational functions which must be performed for the system to successfully complete its mission. The subsystems required to perform those functions are defined as the mission essential subsystems. These mission essential subsystems are classified into three types:

- Time Operating Independent Subsystems. These subsystems are required to operate over a period of time during various mission phases. In addition, each subsystem of this type has the property that a critical failure of that subsystem would degrade the mission below an acceptable level (since each such subsystem must operate without a critical failure these subsystems are independent in the probabilistic sense).

- Single Event Independent Subsystems. These subsystems are required to perform a single operation (or several operations) at a particular time (or times) during the mission. Their operating time is essentially zero, and they have the property that a critical failure of any such subsystem would degrade the mission below an acceptable level.

- Pseudo-Subsystems. The MCSP is the probability that each mission essential function is successfully performed. However, there may be cases when two or more subsystems are not independent but interact in the performance of a given function. It is necessary to define the interrelationship between such subsystems and treat them as a single "subsystem" referred to as a "pseudo-subsystem". A pseudo-subsystem consists of a set of time operating or single event subsystems, referred to as the "elements" of the pseudo-subsystem. The probability that a pseudo-subsystem completes its required function can be calculated according to the defined interdependency and characteristics of its elements. Furthermore, if any elements are improved the increased performance of the pseudo-subsystem can be determined. A pseudo-subsystem will be considered as a single "subsystem" in the MCSP and DSPC models.

The success probability of a pseudo-subsystem in completing its required function is characterized by the property that it is never equal to the product of the success probabilities of its elements. Otherwise the elements would be independent subsystems of the first two types. Therefore, the success probability of the pseudo-subsystem is always greater than the product of the success probabilities of its elements (since the product implies that each element must operate without a critical failure).

As a simple example, suppose a mission function requires that for two specified subsystems at least one must operate successfully (i.e., without a critical failure). Let P_1 denote the success probability of one subsystem and P_2 denote the success probability of the other subsystem. The probability that the mission function is successfully performed is equal to the probability that at least one of the subsystems operates successfully, i.e., $1 - (1-P_1)(1-P_2)$. Thus, these two subsystems are not probabilisticly independent and hence constitute a pseudo-subsystem consisting of two elements. If the mission function required both subsystems to operate successfully then the success probability of that function would be the product P_1P_2. The subsystems, in this case, would not constitute a pseudo-subsystem; they would be independent subsystems of the above types.

3. Subsystem Operating Times. In conjunction with the phases defined in the mission profile, the mission essential subsystem operating times (duty cycles) for each phase are determined, or the phase during which a single event subsystem performs its function is specified. This information is also required for the elements of a pseudo-subsystem.

4. Subsystem Failure Data. For each mission essential subsystem, failure data is required in one of the following forms: If the subsystem is to operate over a period of time, the failure data is usually in the form of mean time between failure (MTBF). For single event subsystems, the failure data is in the form of the ratio of the number of critical failures to the number of trials of the event. For pseudo-subsystems the appropriate failure data is required for each element of the pseudo-subsystem. During the conceptual phase, failure data is usually obtained by such means as estimates based on historical data of similar

subsystems (e.g., AFM 66-1 and Reference 7) or detailed engineering analyses of subsystem components. Other sources of failure data are identified in Reference 8. However, as test results become available the accuracy of the subsystem failure data is continuously being improved, and the methodologies presented in this handbook provide a means for the Program Manager to continuously update the evaluation of system progress on a daily basis as improved data becomes available.

5. Subsystem Failure Criticality Factors. For an essential subsystem operating over a period of time, a failure during the mission does not necessarily mean that the mission would be degraded. It depends upon the type of failure and also upon the mission phase during which the failure occurs. A failure usually requires some maintenance action, but many failure modes have no effect upon mission success, e.g., a loose screw or some other minor failure. The failure criticality factor of a time operating independent subsystem during a particular mission phase is the fraction of total failures occurring during that phase which lead to unacceptable mission degradation. More precisely, it is the conditional probability of unacceptable mission degradation given that the subsystem has a failure during that phase. For a time operating element of a pseudo-subsystem the failure criticality factor is the fraction of failures which lead to unacceptable degradation of that element. The reason that the criticality factors are phase dependent can be made clear by means of an example: A failure of the weapon delivery computer of an attack aircraft is much more likely to degrade (or even abort) the mission if the failure occurs before weapon release than if the failure occurs after departing the target area when the mission is essentially accomplished. An example of failure criticality factors for subsystems of an aircraft on a tactical interdiction mission are presented in Table 3 on page 38.

Failure criticality data can be obtained from failure mode effects analysis, historical data, and data collected during testing in conjunction with the MTBF data. As the accuracy of this data is continuously being improved throughout the program, the models presented in this handbook allow the Program Manager to continuously improve the accuracy of the evaluation of the system.

For single event subsystems only critical failures are considered. Therefore, failure criticality factors are not required for these subsystems.

C. MCSP MODEL DEVELOPMENT

1. Mathematical Basis. In evaluating the reliability of a subsystem, the primary interest is in the probability that the subsystem operates for a certain period of time without a failure, or in the ratio of number of successes to total number of trials for a single event subsystem. Mission requirements and the mission profile determine the operating times or event times within the mission phases. For a subsystem operating for time t during some mission phase, the most commonly used expression for calculating the probability that the subsystem operates for time t (duty cycle for that phase) without a failure of any kind is

$$\exp\left\{-\frac{t}{\tau}\right\} , \qquad \text{(III-1)}$$

where τ is the MTBF of the subsystem. The assumption of the exponential reliability function (III-1) is usually justified, but if a subsystem is known to have a different reliability function, of course it should be used in place of Expression (III-1). The exponential reliability function is justified when the failure rate is constant over the time period of interest. It can be used for the initial approximation, and subsequently changes can be made as better data become available.

Expression (III-1) is the probability that the subsystem operates for time t without a failure of any kind. As discussed above under Subsystem Failure Criticality Factors, not all failures are serious enough to degrade or abort the mission. Therefore, Expression (III-1) must be modified to yield the probability that the subsystem completes its operation for time t without experiencing a critical failure. Let

$$F_c \qquad \text{(III-2)}$$

denote the failure criticality factor of the subsystem (or element of a pseudo-subsystem) during the phase considered in Expression (III-1). Since τ is the subsystem MTBF, the mean time between critical failure, τ_c, (Reference 3) is given by

$$\tau_c = \frac{\tau}{F_c} \quad . \qquad \text{(III-3)}$$

Equation (III-3) shows the purpose of the failure criticality factor. It is used to transform the MTBF to the mean time between critical failure, τ_c. This is necessary for determining the MCSP which is the probability that the system completes its mission without unacceptable degradation due to a critical failure of one or more subsystems. Therefore, the probability that the subsystem operates for time t (during the mission phase under consideration) without a critical failure is

$$\exp\left\{-\frac{t}{\tau_c}\right\} = \exp\left\{-\frac{tF_c}{\tau}\right\} \quad . \qquad \text{(III-4)}$$

As mentioned previously, for the single event subsystems, the failure data is based upon the number of critical failures during a certain number of trials of the event. Thus, for these subsystems, the empirical probability of success is given by

$$\frac{n_s}{N} \quad , \qquad \text{(III-5)}$$

where n_s is the number of successes (non-critical failures) observed and N is the number of trials.

The system MCSP is determined by considering all mission essential subsystems throughout all mission phases. The MCSP model will be developed in the following section.

2. Mathematical Formulation of the MCSP Model. Early in a system program the subsystems are identified; this defines the Baseline System. When the inputs discussed above become available for the mission essential subsystems, the MCSP of the Baseline System can be calculated. Before proceeding with the development

of the MCSP model, the following mathematical notation is introduced which also facilitates the development of the DSPC model. The mathematical notation and equations may at first appear complex; however, the simplicity of the procedure will become apparent by means of examples presented at the end of this section.

N_s ≡ Total number of mission essential subsystems (a pseudo-subsystem is considered as one subsystem).

N_p ≡ Number of mission phases to be considered in calculating the MCSP, i.e., the MCSP through phase N_p. It is sometimes of interest to make MCSP calculations for values of N_p less than the total number of mission phases defined in the mission profile. In this way, the system MCSP can be analyzed through any phase.

$t_i(j)$ ≡ Operating time (hours) of subsystem i during mission phase j. For a single event subsystem, operating times are not required (can be considered 0), but the phase when the event is to occur must be specified.

$\tau_i^{(o)}$ ≡ Mean time (hours) between failure (MTBF) of subsystem i. This is required for time operating independent subsystems. The superscript o is used to indicate that the value refers to the baseline subsystem; if subsystem options become available the superscript will assume other values.

$F_{ci}^{(o)}(j)$ ≡ Failure criticality factor of subsystem i during phase j ($j = 1, 2, \ldots, N_p$). It is the conditional probability of unacceptable mission degradation given that the subsystem experiences a failure during phase j (refer to discussion on page 25). These values are required only for subsystems for which a value of $\tau_i^{(o)}$ has been assigned.

$P_i^{(o)}(j)$ $\equiv$ Conditional probability that subsystem i completes its required function during phase j without a critical failure given that no mission essential subsystem has experienced a critical failure prior to phase j.

$P_i^{(o)}$ $\equiv$ Probability that subsystem i completes its required functions through phase N_p without a critical failure (given that no other mission essential subsystem has experienced a critical failure).

P_{co} $\equiv$ The Baseline System MCSP. This is the probability that all N_s essential subsystems complete their required function (through phase N_p) without experiencing a critical failure.

To calculate the MCSP it is necessary to calculate (for each subsystem and each mission phase) the probability that the subsystem performs its function without a critical failure. These quantities $P_i^{(o)}(j)$ are calculated as follows:

a. If subsystem i is a time operating independent subsystem (applying the exponential reliability distribution discussed on pages 25 and 26),

$$P_i^{(o)}(j) = \exp\left\{- \frac{t_i(j)\ F_{ci}^{(o)}(j)}{\tau_i^{(o)}}\right\} . \qquad \text{(III-6a)}$$

b. If subsystem i is a single event independent subsystem performing a function during phase j (refer to discussion on pages 23 and 26),

$$P_i^{(o)}(j) = \frac{n_{si}(j)}{N_i(j)} \qquad \text{(III-6b)}$$

which is the ratio of the number of successes to the number of trials of the event during phase j (if the single event subsystem does not perform a function during phase j then $P_i^{(o)}(j)$ is equal to 1). This ratio can be obtained from estimates based on historical data, engineering estimates, test results or other means.

c. If subsystem i is a pseudo-subsystem the value of $P_i^{(o)}(j)$ must be calculated according to the defined interdependency of its elements. In addition, the operating time and the mean time between critical failure must be specified for each time operating element of the pseudo-subsystem; and for the single event elements the ratio of the number of successes to the number of trials must be specified.

Once the probabilities $P_i^{(o)}(j)$ for subsystem i are determined for each mission phase, the subsystem mission success probabilities can be concisely expressed as the product (since the subsystem must successfully complete its functions during each mission phase)

$$P_i^{(o)} = \prod_{j=1}^{N_P} P_i^{(o)}(j) \qquad (i = 1, 2, \ldots, N_S) \quad , \tag{III-7}$$

and the Baseline System MCSP (all subsystems successfully complete their functions) is given by

$$P_{co} = \prod_{i=1}^{N_s} P_i^{(o)} \tag{III-8}$$

The above expressions are the fundamental equations for MCSP modeling; furthermore, when test results become available empirical probabilities of subsystem mission success can be used directly in Equation (III-7) for the calculation of the Baseline System MCSP.

In Section III-E some detailed numerical examples will be presented to illustrate the simplicity in applying the above described mathematical procedure.

D. MCSP MODEL OUTPUTS

1. <u>Baseline System MCSP</u>. The primary output of the MCSP model is the Baseline System MCSP as determined by Equation (III-8). This value provides a measure of total system reliability and provides the potential user with early insight into the operational suitability of the system from the reliability standpoint.

2. Critical Subsystem Ranking. The quantitative ranking of the most critical subsystems is obtained by ordering the values of $1 - P_i^{(o)}$, i.e., the conditional probability that subsystem i experiences a critical failure during the mission given that no other subsystem has failed. This identifies those subsystems with the greatest likelihood of degrading the system below acceptable limits.

3. Sensitivity Analysis of Subsystem Improvement. A sensitivity analysis can be performed to show MCSP enhancement as a function of the improvement of one or more subsystems. If, for example, the performance of subsystem i is improved from $P_i^{(o)}$ to $P_i^{(1)}$, then from (III-8) it follows that the Baseline MCSP is increased to

$$P_{co}\left(\frac{P_i^{(1)}}{P_i^{(o)}}\right), \tag{III-9}$$

since the factor in parenthesis removes $P_i^{(o)}$ and replaces it by $P_i^{(1)}$ in equation (III-8). In many cases, it is of interest to show MCSP improvement as a function of increased MTBF of a subsystem. Equations (III-6a) and (III-7) together with the procedure described by Expression (III-9) can be used to show the impact on system MCSP due to improving the MTBF of a subsystem. The MCSP eventually becomes essentially insensitive to further improvements in subsystem MTBF. This is helpful in establishing realistic subsystem MTBF goals, which in turn can be used to establish realistic system MTBF goals.

4. Probability of Successful Subsystem Operation. The subsystem mission success probability can be examined either for a particular mission phase as given by $P_i^{(o)}(j)$ or for any number of consecutive phases by changing N_p in Equation (III-7). This is sometimes of interest since it shows quantitatively the individual phases or the cumulative phases during which the greatest number of failures occur.

For a pseudo-subsystem, an improvement of any of its elements leads to an increase in its original value of $P_i^{(o)}$; this new value is calculated as described previously. The impact on the system MCSP due to reliability improvements of any elements of a pseudo-subsystem can then be determined from Expression (III-9).

5. Probability of No Subsystem Failure. Another important measure attached to a system is the probability that the system completes its mission without a failure (of any type) of any essential subsystem or any element of a pseudo-subsystem. This measure is important for maintenance, logistic support cost, life cycle cost and availability considerations. This probability is easily obtained by the same procedure described for calculating the MCSP with the following simplifications:

a. For any pseudo-subsystem, consider its elements as independent subsystems of the first two types discussed on page 22; and change N_s accordingly to account for these additional subsystems.

b. Set all failure criticality factors equal to 1 (this eliminates the problem of determining failure criticality factors).

c. Apply equations (III-6a), (III-6b), (III-7) and (III-8).

E. MCSP EXAMPLES

1. Target Activated Munitions. A hypothetical mine system is analyzed in this example to illustrate the approach to be followed in applying the MCSP methodology. A more complete analysis of an actual target activated munitions system (Grasshopper Mine) can be found in Reference 4.

The mission profile of the mine is shown pictorially in Figure 5. Table 1 identifies the mission essential subsystems together with their performance characteristics during each phase. The Cutter, Fin, Brake, Body, and Warhead are examples of single event subsystems, whereas some of the electronic subsystems must operate over a period of time (i.e., duty cycle of 240 hours).

The $P_i^{(o)}(j)$ values (estimates or test results) for the single event subsystems are listed in Table 1. The probability that the other subsystems successfully complete their required functions were calculated using Equation (III-4). For example, using the values from Table 1, the probability that Sensor B performs its function without an abort causing failure is given by

$$\exp\left\{- \frac{240\ (.5)}{3000}\right\} = \exp\left\{- .04\right\} = .96 \qquad \text{(III-10)}$$

which appears in Table 2.

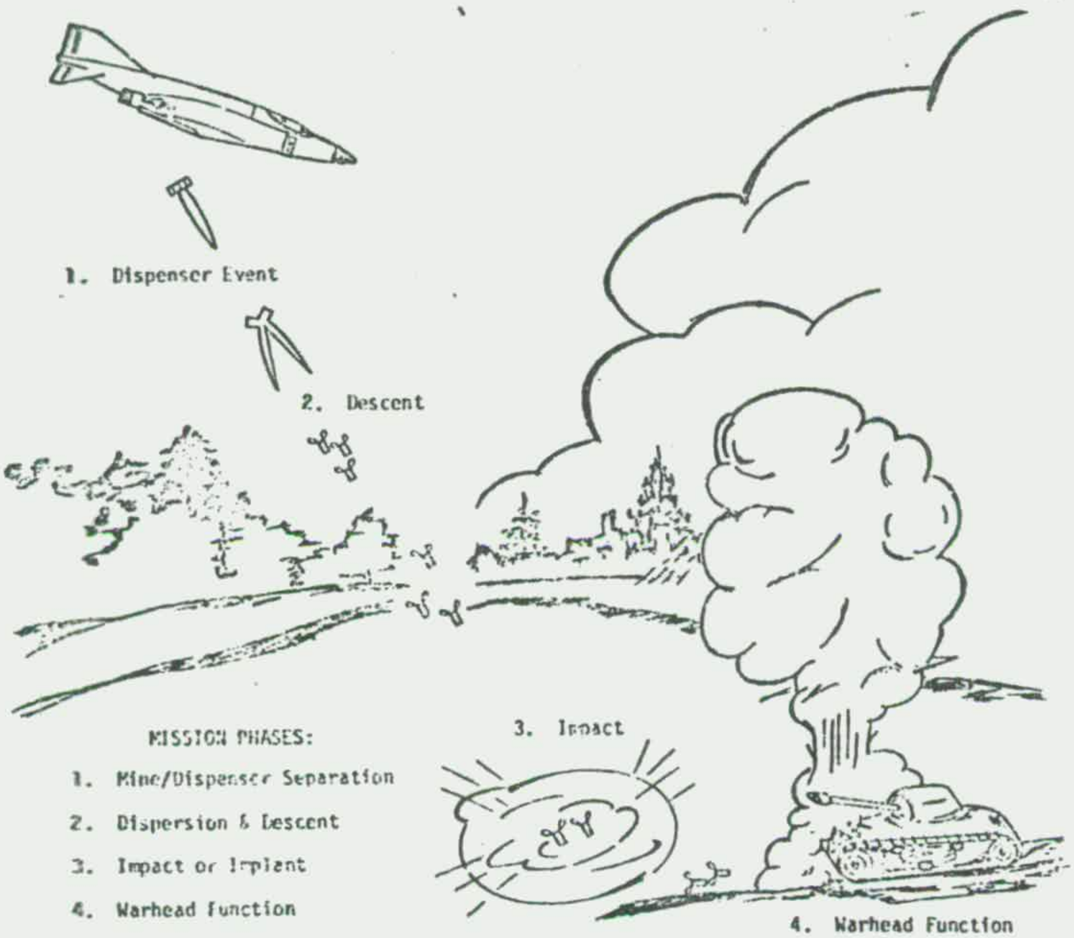


Figure 5. Mine Mission Profile

Table 1

CHARACTERISTICS OF MINE BASELINE SYSTEM

MISSION ESSENTIAL SUBSYSTEMS	PHASE 1	PHASE 2	PHASE 3	PHASE 4			PHASE 5
	MINE/DISPENSER SEPARATION SUCCESS	DESCENT SUCCESS	IMPLANT SUCCESS	TARGET IDENTIFICATION			CONDITIONAL DETONATION SUCCESS
				MTBF (Hrs)	F_C	OPERATING TIME (Hrs)	
WARHEAD	---	----	---	---	---	---	.98
STRUCTURE							
Cutter	.80	----	---	---	---	---	---
Fin	---	.70	---	---	---	---	---
Brake	---	----	.75	---	---	---	---
Body	.98	1.00	.90	---	---	---	---
FUZE ASSEMBLY							
Sensor A	---	----	---	5,000	.5	240	---
Sensor B	---	----	---	3,000	.5	240	---
PROCESSOR	---	----	---	2,500	1.0	240	---
BATTERY	---	----	---	2,500	1.0	240	---
SAFE & ARM	---	.95	.95	---	---	---	---
STRUCTURE & HARNESS	---	----	---	35,000	1.0	240	---

In Table 2 the MCSP is presented together with a ranking of the subsystems in terms of their likelihood of experiencing a critical failure during the mission. Taking the product of the probabilities listed in the table yields an MCSP of .25. In the case of a mine, the interpretation of MCSP is the probability that the mine is still in operative condition up to a specified length of time (which in this example is 240 hours) given that it was not activated by a target.

Table 2

MCSP AND CRITICAL SUBSYSTEM RANKING OF MINE BASELINE SYSTEM

SUBSYSTEM	PROBABILITY OF SUCCESSFULLY PERFORMING ITS FUNCTION ($P_i^{(o)}$)	RANKING OF CRITICAL SUBSYSTEMS
FIN	.70	1
BRAKE	.75	2
CUTTER	.80	3
BODY	.88	4
SAFE & ARM	.90	5
BATTERY	.91	6
PROCESSOR	.91	7
SENSOR B	.96	8
SENSOR A	.98	9
WARHEAD	.98	10
STRUCTURE & HARNESS	.99	11
	$\text{MCSP} = \prod_{i=1}^{11} P_i^{(o)} = .25$	

Figure 6 is presented to show a sensitivity analysis of the Fin which is the most critical subsystem. It shows the MCSP enhancement resulting from improvement of the Fin holding all other subsystem probabilities constant. The improvement of only the Fin can increase the MCSP from its Baseline value of .25 to a maximum of .36. Any further MCSP enhancement would require improvements of additional subsystems. A similar sensitivity analysis can be performed for any other subsystem or combination of subsystems.

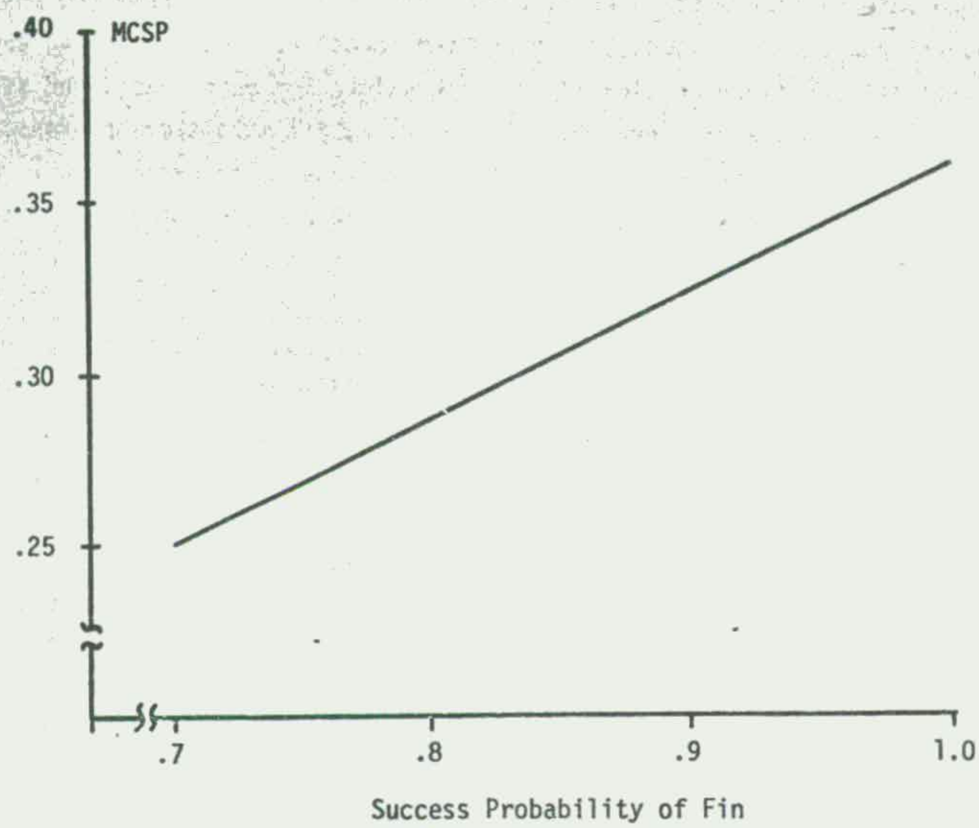


Figure 6. Sensitivity Analysis of Fin.

In Sections IV and V, this mine example will be continued and extended by considering subsystem options to illustrate the application of the DSPC and DSPCE methodologies.

The following section presents a detailed application of the MCSP model to an aircraft system.

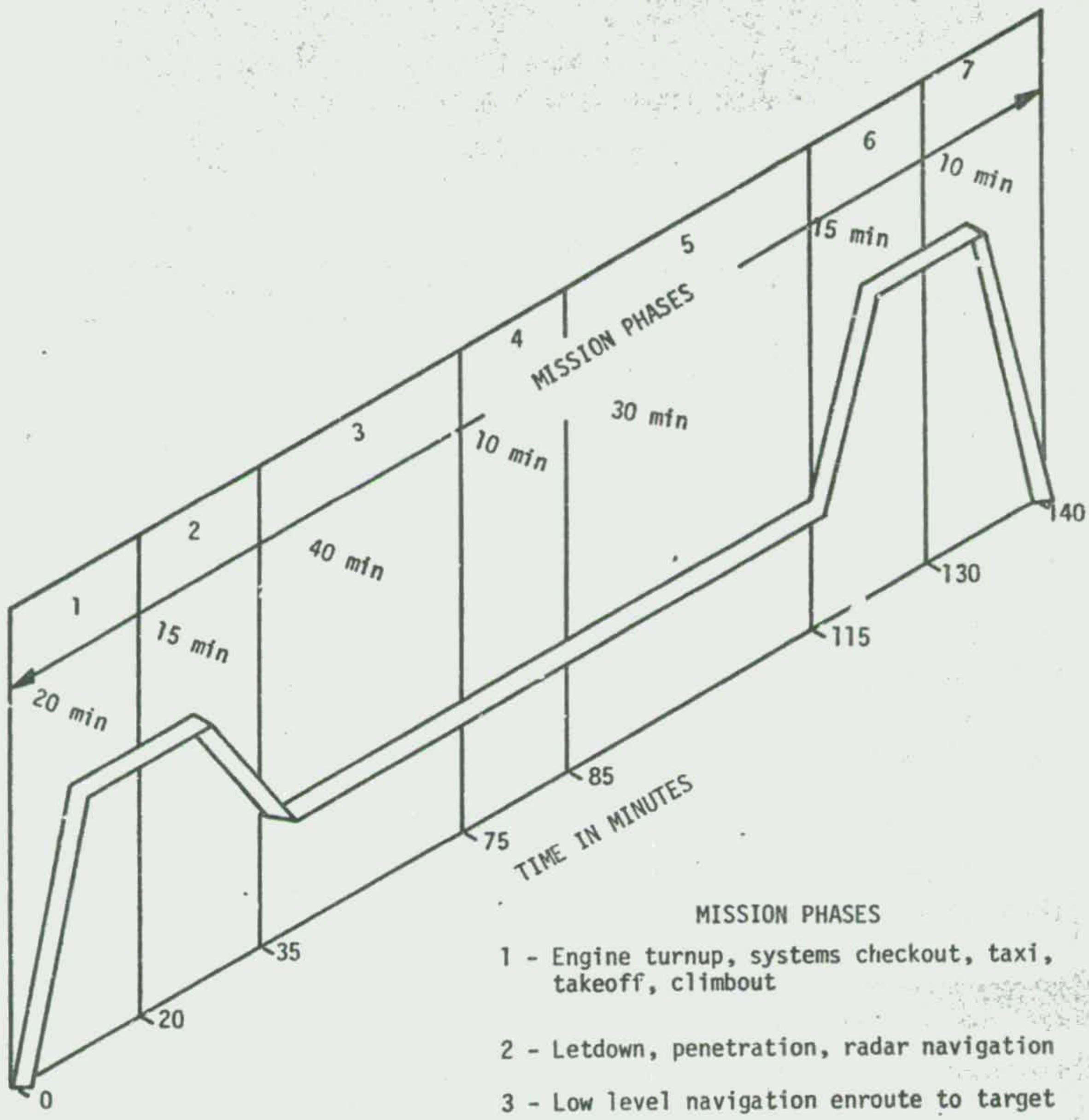
2. Tactical Fighter Bomber. This example illustrates the application of MCSP techniques to a much larger system and shows the interrelationship of MTBFs, criticality factors, and operating times in determining the system MCSP. The data have been extracted from existing sources, and the example serves to demonstrate the methodology and the availability of data for the models.

The Interdiction Mission Profile is shown in Figure 7. From the phase times and the phase descriptions, the subsystem functions required during each phase, qualitative failure criticality considerations for each phase, and subsystem operating times are determined. For example, all subsystems are assumed to be operating during the ground checkout during Phase 1 and certain failures detected at this time could abort the mission even though the actual subsystem function is not required until a later phase.

Table 3 lists the mission essential subsystems and the associated reliability data. This data was extracted from the AFM 66-1 maintenance data system as reported in the Maintainability Reliability Summary (DD 56 B5527). Of all the AFM 66-1 reports (DD 56), the Maintainability Reliability Summary is the best source of failure data for MCSP calculations for Air Force aircraft weapon systems. This summary provides the failure rate (reciprocal of MTBF) for each subsystem, the abort rate, and a description of the failures from which the failure criticality factor can be derived. Some subsystems such as the Airframe, Escape Capsule, Air Conditioning, etc., impact the MCSP only if the subsystem failure causes an abort. Therefore, for these subsystems, the failure criticality factor is derived from the abort rate. Other subsystems, such as the Flight Controls, Propulsion, Electrical Power, etc., could experience failures which do not necessarily abort the mission but seriously degrade system capability. For these subsystems, the failure criticality factor is derived from the failure description data for mission phases up through the target phase and from the abort rate for mission phases after the target phase. Table 3 illustrates the phase dependency of the criticality factors, e.g., the ECM subsystem is most critical penetrating hostile territory while the Fire Control and Weapons Delivery subsystems are most critical over the target area.

In Table 4, the subsystem operating times or duty cycles are presented. In this example, for ease of calculation, if subsystems are operated at all during a particular phase, they are assumed to operate for the entire phase. This is not generally the case in actual operations; for example, even though a subsystem operates during the ground check, it does not necessarily operate throughout Phase 1 which also includes taxi, takeoff, and climbout. Duty cycle variations are easily adjusted in Equation (III-6a) when subsystem operating times are not equal to mission phase times.

Using the data presented in Tables 3 and 4, MCSP calculations can be made as follows:



MISSION PHASES

1 - Engine turnup, systems checkout, taxi, takeoff, climbout

2 - Letdown, penetration, radar navigation

3 - Low level navigation enroute to target

4 - Target acquisition, bomb releases

5 - Depart target, low level navigation through egress

6 - Depart hostile territory, climbout, navigation enroute to base

7 - Approach, landing, engine shutdown

Figure 7. Tactical Interdiction Mission Profile.

Table 3

TYPICAL FIGHTER-BOMBER RELIABILITY DATA

SOURCE: AFM 66-1

MISSION ESSENTIAL SUBSYSTEMS	MTBF (Hrs)	FAILURE CRITICALITY FACTORS						
		MISSION PHASES						
		1	2	3	4	5	6	7
AIRFRAME	14	.003	.003	.003	.003	.003	.003	.003
LANDING GEAR	13	.382	.013	.013	.013	.013	.013	.382
FLIGHT CONTROLS	10	.370	.370	.370	.370	.370	.026	.026
ESCAPE CAPSULE	29	.006	.006	.006	.006	.006	.006	.006
PROPULSION	32	.492	.492	.492	.492	.492	.032	.032
AIR CONDITIONING	22	.014	.014	.014	.014	.014	.014	.014
ELECTRICAL POWER	48	.552	.552	.552	.552	.552	.035	.035
LIGHTING	20	.002	.002	.002	.002	.002	.002	.002
HYDRAULIC/PNEUMATIC	18	.818	.818	.818	.818	.818	.021	.021
FUEL	21	.025	.025	.025	.025	.025	.025	.025
OXYGEN	63	.006	.006	.006	.006	.006	.006	.006
MISC UTILITIES	70	.011	.011	.011	.011	.011	.011	.011
INSTRUMENTS	19	.014	.014	.014	.014	.014	.014	.014
AUTO PILOT	14	.054	.054	.054	.054	.054	.054	.054
HF COMMUNICATIONS	68	.680	.680	.680	.680	.680	.004	.004
UHF COMMUNICATIONS	43	.398	.398	.398	.398	.398	.016	.016
INTERPHONE	81	.491	.491	.491	.491	.491	.010	.010
IFF	80	.630	.630	.630	.630	.630	.012	.012
RADIO NAVIGATION	42	.001	.001	.001	.001	.001	.001	.001
BOMB/NAVIGATION	6	.750	.750	.750	.750	.500	.019	.019
FIRE CONTROL	97	.001	.001	.001	.220	.001	.001	.001
WEAPONS DELIVERY	31	.005	.005	.005	.352	.005	.005	.005
ECM	13	.001	.001	.236	.236	.236	.001	.001

Table 4

FIGHTER-BOMBER MISSION ESSENTIAL SUBSYSTEM OPERATING TIMES

MISSION ESSENTIAL SUBSYSTEMS	$t_i(j)$ (Hours)						
	FHASES						
	1	2	3	4	5	6	7
AIRFRAME	.33	.25	.67	.17	.50	.25	.17
LANDING GEAR	.33	0.00	0.00	0.00	0.00	0.00	.17
FLIGHT CONTROLS	.33	.25	.67	.17	.50	.25	.17
ESCAPE CAPSULE	.33	.25	.67	.17	.50	.25	.17
PROPULSION	.33	.25	.67	.17	.50	.25	.17
AIR CONDITIONING	.33	.25	.67	.17	.50	.25	.17
ELECTRICAL POWER	.33	.25	.67	.17	.50	.25	.17
LIGHTING	.33	.25	.67	.17	.50	.25	.17
HYDRAULIC/PNEUMATIC	.33	.25	.67	.17	.50	.25	.17
FUEL	.33	.25	.67	.17	.50	.25	.17
OXYGEN	.33	.25	.67	.17	.50	.25	.17
MISC UTILITIES	.33	.25	.67	.17	.50	.25	.17
INSTRUMENTS	.33	.25	.67	.17	.50	.25	.17
AUTO PILOT	.33	.25	.67	.17	.50	.25	.17
HF COMMUNICATIONS	.33	.25	.67	.17	.50	.25	.17
UHF COMMUNICATIONS	.33	.25	.67	.17	.50	.25	.17
INTERPHONE	.33	.25	.67	.17	.50	.25	.17
IFF	.33	.25	.67	.17	.50	.25	.17
RADIO NAVIGATION	.33	.25	.67	.17	.50	.25	.17
BOMB/NAVIGATION	.33	.25	.67	.17	.50	.25	.17
FIRE CONTROL	.33	0.00	0.00	.17	0.00	0.00	0.00
WEAPONS DELIVERY	.33	0.00	0.00	.17	0.00	0.00	0.00
ECM	.33	.25	.67	.17	.50	0.00	0.00

The probability that a particular subsystem successfully performs its function during a particular phase is given by Equation (III-6a). For example, the probability that the Airframe subsystem successfully completes its function during Phase 1 of the mission is

$$
\begin{aligned}
P_1^{(o)}(1) &= \exp\left\{-\frac{t_1(1)F_{c1}^{(o)}(1)}{\tau_1^{(o)}}\right\} \\
&= \exp\left\{-\frac{(.33)\ (.003)}{14}\right\} \qquad \text{(III-11)} \\
&= .9999 \quad .
\end{aligned}
$$

Similar calculations are made for each subsystem for each phase. These results are displayed in the first 7 columns of Table 5.

The probability that a particular subsystem successfully completes its function throughout the entire mission is given by Equation (III-7). For example, the probability that the Airframe subsystem successfully completes the mission is

$$
\begin{aligned}
P_1^{(o)} &= \prod_{j=1}^{7} P_1^{(o)}(j) \\
&= (.9999)^7 \qquad \text{(III-12)} \\
&= .9993 \quad .
\end{aligned}
$$

Similar calculations are made for the other subsystems, and these results are displayed in the last column of Table 5.

The MCSP for the interdiction mission depicted in Figure 7 is given by Equation (III-8),

Table 5

FIGHTER-BOMBER BASELINE SYSTEM MCSP RESULTS

MISSION ESSENTIAL SUBSYSTEMS	$P_i^{(o)}(j)$ PHASES 1	2	3	4	5	6	7	$P_i^{(o)}$
AIRFRAME	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9993
LANDING GEAR	.9903	1.0000	1.0000	1.0000	1.0000	1.0000	.9951	.9855
FLIGHT CONTROLS	.9870	.9908	.8756	.9939	.9816	.9994	.9996	.9305
ESCAPE CAPSULE	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9993
PROPULSION	.9949	.9962	.9898	.9974	.9923	.9998	.9998	.9705
AIRCONDITIONING	.9998	.9998	.9996	.9999	.9997	.9998	.9999	.9985
ELECTRICAL POWER	.9962	.9971	.9924	.9981	.9943	.9998	.9999	.9780
LIGHTING	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9993
HYDRAULIC/PNEUMATIC	.9850	.9887	.9702	.9925	.9775	.9997	.9998	.9162
FUEL	.9996	.9997	.9992	.9998	.9994	.9997	.9998	.9972
OXYGEN	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9993
MISC UTILITIES	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9993
INSTRUMENTS	.9998	.9998	.9995	.9999	.9996	.9998	.9999	.9983
AUTO PILOT	.9987	.9990	.9974	.9994	.9981	.9990	.9994	.9910
HF COMMUNICATIONS	.9967	.9975	.9934	.9983	.9950	.9999	.9999	.9808
UHF COMMUNICATIONS	.9969	.9977	.9938	.9985	.9954	.9999	.9999	.9822
INTERPHONE	.9980	.9985	.9960	.9990	.9970	.9999	.9999	.9884
IFF	.9994	.9980	.9948	.9987	.9961	.9999	.9999	.9849
RADIO NAVIGATION	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9993
BOMB/NAVIGATION	.9592	.9692	.9200	.9794	.9592	.9992	.9994	.8024
FIRE CONTROL	.9999	1.0000	1.0000	.9996	1.0000	1.0000	1.0000	.9995
WEAPONS DELIVERY	.9999	1.0000	1.0000	.9981	1.0000	1.0000	1.0000	.9980
ECM	.9999	.9999	.9880	.9970	.9910	1.0000	1.0000	.9760
$P_c^{(o)}(j)$	.9031	.9330	.8278	.9432	.8898	.9952	.9916	.5777
$P_c^{(o)}(n)$	.9031	.8426	.6975	.6579	.5854	.5826	.5777	

$$P_c^{(o)} = \prod_{i=1}^{23} P_i^{(o)} = .5777 \quad . \qquad \text{(III-13)}$$

This value is the product of the entries in the last column of Table 5.

Sometimes it is of interest to examine the system MCSP on a phase-by-phase basis. This can be calculated by

$$P_c^{(o)}(j) = \prod_{i=1}^{N_s} P_i^{(o)}(j) \quad , \qquad \text{(III-14)}$$

where the notation $P_c^{(o)}(j)$ has been introduced to designate the system MCSP for a particular phase. These values were calculated for this example and are displayed in the next to last row in Table 5. Also of interest is the cumulative MCSP for the entire system up through any phase n. This is given by

$$P_c^{(o)}(n) = \prod_{j=1}^{n} P_c^{(o)}(j) \quad , \quad 1 \leq n \leq N_p \; . \qquad \text{(III-15)}$$

These values are displayed in the last row of Table 5 where the system MCSP is obtained for $n = N_p$.

The MCSP value (.5777) obtained in this example should be interpreted very carefully. It is strictly a measure of system reliability for this particular mission and does not measure mission effectiveness. (MCSP results would generally be used as inputs in effectiveness calculations.) The results indicate that, on the average, approximately 58 percent of the attack force would complete the mission without any serious failures. This part of the force would be expected to destroy their targets to the level commensurate with their weapons and delivery conditions. This does not necessarily mean that the other 42 percent of the force inflict no damage at all. On the average, 42 percent of the force would be operating with certain equipments in degraded modes. However, depending on the particular malfunctions, and the skill and ingenuity of the aircrew, significant target destruction would also be accomplished by this portion of force.

Table 5 lists the subsystem reliabilities defined in terms of MCSP along with the overall system MCSP. The next output of the MCSP model is the critical subsystem ranking. As discussed previously, $P_i^{(o)}$ is the probability that a subsystem successfully performs its function during a mission. Thus,

$$1 - P_i^{(o)} \tag{III-16}$$

is the probability that the mission is unacceptably degraded because of subsystem i experiencing a critical failure during the mission. The critical subsystem ranking is obtained by subtracting the $P_i^{(o)}$ values in the last column of Table 5 from unity and then ordering the values obtained. Thus for the Bomb/Navigation subsystem

$$1 - P_i^{(o)} = 1 - .8024 = .1976 \quad . \tag{III-17}$$

Similar values were obtained for the other subsystems, and these values were then ranked as shown in Table 6. For comparison purposes, the mission essential subsystems for this example are ranked by MTBF on the left hand side of the table. Table 6 clearly shows that the Bomb/Navigation subsystem has the greatest impact on mission success. Perhaps, this would have also been evident simply on the basis of its low MTBF value and its mission essential functions, and therefore analytical techniques would not be necessary to generate this type of information. However, the MCSP methodology not only quantifies a subsystem's impact on mission success; but in addition, the critical subsystem ranking is the best indicator of the effect a subsystem will have on the mission from a reliability standpoint. This is demonstrated in Table 6, where the subsystem MTBF ranking agrees with the criticality ranking only for the Bomb/Navigation subsystem. The significance of this type of comparison is readily seen in the case of the Hydraulic/Pneumatic subsystem which is ranked seventh by MTBF but second by mission criticality. Hence, this MCSP model output identifies those subsystems whose improvement most enhances probability of mission completion, and the subsystems so identified are not necessarily those with lowest MTBF.

Table 6

FIGHTER-BOMBER MTBF AND CRITICAL SUBSYSTEM RANKING

MTBF RANKING			CRITICAL SUBSYSTEM RANKING		
RANK	SUBSYSTEM	MTBF (Hrs)	RANK	SUBSYSTEM	$1 - P_i^{(o)}$
1	BOMB/NAVIGATION	6	1	BOMB NAVIGATION	.1976
2	FLIGHT CONTROLS	10	2	HYDRAULIC/PNEUMATIC	.0838
3	LANDING GEAR	13	3	FLIGHT CONTROLS	.0695
4	ECM	13	4	PROPULSION	.0295
5	AIRFRAME	14	5	ECM	.0240
6	AUTO PILOT	14	6	ELECTRIC POWER	.0220
7	HYDRAULIC/PNEUMATIC	18	7	HF COMMUNICATIONS	.0192
8	INSTRUMENTS	19	8	UHF COMMUNICATIONS	.0178
9	LIGHTING	20	9	IFF	.0151
10	FUEL	21	10	LANDING GEAR	.0145
11	AIR CONDITIONING	22	11	INTERPHONE	.0116
12	ESCAPE CAPSULE	29	12	AUTO PILOT	.0090
13	WEAPONS DELIVERY	31	13	FUEL	.0028
14	PROPULSION	32	14	WEAPONS DELIVERY	.0020
15	RADIO NAVIGATION	42	15	INSTRUMENTS	.0017
16	UHF COMMUNICATIONS	43	16	AIR CONDITIONING	.0015
17	ELECTRIC POWER	48	17	AIRFRAME	.0007
18	OXYGEN	63	18	ESCAPE CAPSULE	.0007
19	HF COMMUNICATIONS	68	19	MISC UTILITIES	.0007
20	MISC UTILITIES	70	20	LIGHTING	.0007
21	IFF	80	21	OXYGEN	.0007
22	INTERPHONE	81	22	RADIO NAVIGATION	.0007
23	FIRE CONTROL	97	23	FIRE CONTROL	.0005

The final output of MCSP modeling is the sensitivity analysis, a sample of which is shown in Figure 8. The MTBFs of the two most critical subsystems are varied up to twice their baseline values, and corresponding MCSP calculations using Expression (III-9) are made. (The input data for the other mission essential subsystems are held constant at the baseline values.) The MCSP enhancement due to MTBF improvement of the Bomb/Navigation and Hydraulic/Pneumatic subsystems is considered separately and in combination. For comparison purposes, the sensitivity analysis has also been performed for the Weapons Delivery subsystem which is seen to have virtually no impact on total system MCSP enhancement. This might at first seem somewhat surprising since the Weapons Delivery subsystem performs such an important function during the mission and its MTBF is lower than some of the other subsystems which are ranked higher in terms of mission criticality. The answer, of course, lies in the total operating time of the Weapons Delivery subsystem which is considerably less than the operating times for the Bomb/Navigation and Hydraulic/Pneumatic subsystems. This emphasizes the dependence of MCSP on the interrelationship of MTBF, failure criticality, and operating time, i.e., all three of the above parameters must be considered and focusing on only one, such as MTBF, can sometimes be very misleading.

Another important result of the type of analysis displayed in Figure 8 is the establishment of realistic reliability goals for the individual subsystems as well as the total system. For example, the MCSP curve due to improvements in the MTBF of the Hydraulic/Pneumatic subsystem has essentially leveled off for MTBF increases above 80 percent of the baseline value. This establishes a realistic MTBF value for this subsystem for this mission. When similar sensitivity analyses are performed for all the mission essential subsystems, realistic MTBF levels can be determined for all subsystems which in turn establishes the most realistic MTBF for the entire system. The sensitivity analysis curve for many of the subsystems will be similar to that of the Weapons Delivery subsystem which indicates that the Baseline System MTBFs for these subsystems are already adequate for the mission. It should be emphasized that these sensitivity results are very much dependent on the particular mission considered. Therefore, in practice, the most stringent mission that the equipment is expected to perform should be used with the sensitivity analysis in the establishment of realistic MTBF goals.

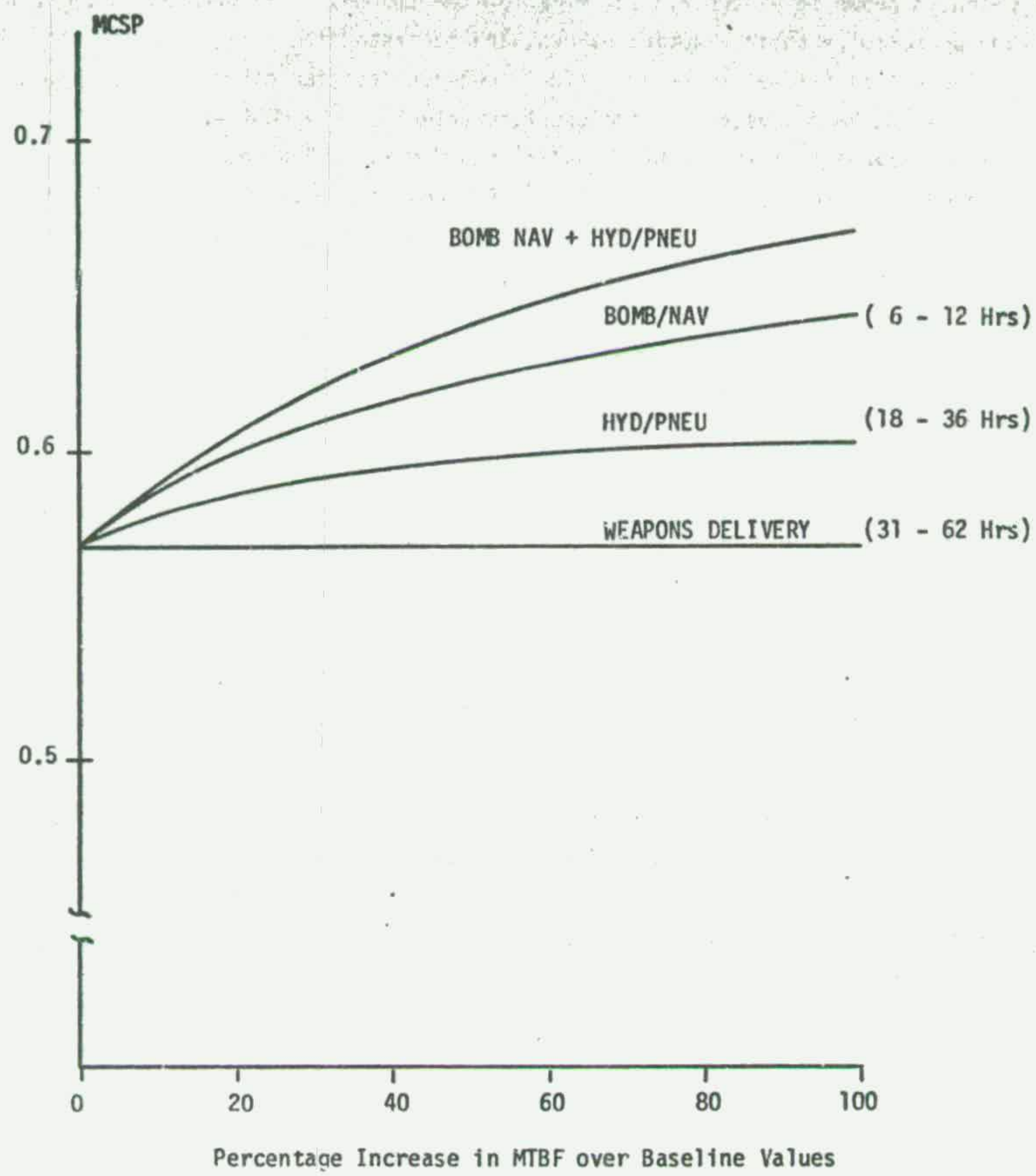


Figure 8. Evaluation of Critical Subsystem Improvement.

F. CONCLUSION

This section has presented the development of the MCSP methodology along with examples of applications of the methodology. From the diversity of the examples, it is readily apparent that the methodology has wide applicability and can provide Program Managers and Decision Makers with valuable information on the operational suitability of their system from a reliability standpoint.

The next section extends this methodology to include a procedure for optimally allocating resources whenever reliability improvement options are available.

SECTION IV

DESIGNING TO SYSTEM PERFORMANCE/COST MODEL

A. GENERAL

The DSPC model was briefly described in Section II-C. This model selects from a group of candidate components and subsystems those to be most effectively integrated into a system design. The various candidate components and subsystems represent options that enable the program engineer to establish different levels of operational capability and reliability associated with the characteristics and cost of the specific options. The DSPC model can be used in the preliminary design of weapon systems. In common practice, preliminary design activities have concentrated on selecting components and subsystems to develop a baseline design that would assure required operational capabilities, such as speed, payload, range, guidance accuracy, etc. It became common practice to make design tradeoffs between capability and cost before the design-to-cost concepts were implemented. With cost in DTC defined to mean Life Cycle Costs, new emphasis must be placed on system reliability since it is a major factor in determining the operating and maintenance costs throughout the life of the system.

The MCSP model was initially developed to show the impact of reliability on operational capability and to show the reliability growth of the total system as the system matured. The DSPC methodology is based upon MCSP as the measure of merit to be used to relate cost and reliability to an indicator of operational capability. Since the DTC approach has been applied to systems in various phases of the acquisition cycle, the DSPC model has most frequently been used to consider reliability improvement of an existing or baseline design as a means to reduce operation and maintenance cost and hence life cycle cost. Thus, the DSPC methodology will usually be referred to in its application to system reliability improvement.

The mathematics of the DSPC model must be easily understood and employed in order to be of value to a System Program Manager or project engineer. For this reason, in addition to the mathematical description, some numerical examples will be worked out in detail to clarify the step-by-step calculations required to develop the DSPC curve illustrated in Figure 2, page 15. The DSPC

curve is defined by a series of vertex points each of which corresponds to a unique combination of subsystem options that produces the maximum MCSP for the associated cost. This combination associated with a vertex point is called an optimal system configuration. The detailed examples should clarify the procedures so that program engineers can apply the methodology to their particular system.

B. SUBSYSTEM RELIABILITY IMPROVEMENT OPTIONS

Weapon system capability, complexity, and cost have increased dramatically. As complexity has increased reliability has become a real concern because, no matter how well a system meets operational requirements, it is of little value if it cannot complete the mission when it is needed. Neither is it of value if the cost to purchase it or the cost to maintain it are not affordable. The DSPC methodology provides a means to assess total system reliability and investment to improve reliability.

In order to use the DSPC methodology, it is necessary to assume that a Baseline System has been configured and that it meets some threshold of operational performance. Given that the initial design or Baseline System meets operational requirements but a low MCSP indicates questionable reliability, it may be necessary to initiate a reliability improvement program. Reliability improvement techniques include the following:

- Screening - Screening entails replacing low reliability components with higher reliability components. This is usually accomplished by test selection in which higher performance criteria are imposed in testing than the component is expected to encounter in the intended operation.

- Design Modification - In this technique minor changes are made in the subsystem design. These include such things as substituting an integrated circuit for a number of discrete parts, etc.

- Environmental Protection - Environmental protection involves such things as the installation of shock mounts, climate controlled compartments, etc.

- **Redundancy - When volume and weight constraints allow, duplicate or back-up subsystems can be installed.**

- Subsystem Redesign - Subsystem redesign involves development of a completely new subsystem to perform the required function, or major modifications in the design of an existing subsystem.

The various reliability levels (subsystem performance) and their corresponding costs constitute the subsystem options. For subsystems operating over a period of time, the reliability improvement options are obtained by increasing the MTBF (over the baseline values). For single event subsystems, the reliability improvement options are obtained by increasing the number of successes per number of trials (over the baseline values). For pseudo-subsystems, the reliability improvement options are obtained by increasing the performance of pseudo-subsystem elements. It is assumed at this point that the Program Manager has received options for some of the mission essential subsystems in the form of cost and performance estimates which define each option.

To implement the DSPC model, the subsystem reliability improvement options must be quantified. This necessitates the introduction of the following notation:

P_{co} $\equiv$ MCSP of the Baseline System.

C_o $\equiv$ Unit acquisition cost of the Baseline System.

$C_i^{(o)}$ $\equiv$ Unit acquisition cost of the i-th essential subsystem of the Baseline System.

$n(i)$ $\equiv$ Number of options available for subsystem i.

$P_i^{(\ell)}$ $\equiv$ Probability that the ℓ-th option ($\ell=1,2,\ldots, n(i)$) for subsystem i completes its required function (independent of the other subsystems).

$C_i^{(\ell)}$ $\equiv$ Unit acquisition cost of the ℓ-th option ($\ell=1,2, \ldots, n(i)$) for subsystem i.

P_{cj} ≡ MCSP of the system configuration corresponding to the j-th optimal vertex point of the DSPC curve.

C_j ≡ Unit acquisition cost of the system configuration corresponding to the j-th optimal vertex point of the DSPC curve.

As can be seen by the above notation, the DSPC model will be developed in terms of acquisition costs. This is the simplest manner in which to illustrate the methodology. However, the same DSPC optimization procedure is applicable when the above costs are defined as acquisition costs plus logistics support costs or life cycle costs.

To clarify this notation, the symbols

$$P_i^{(2)} \quad \text{and} \quad C_i^{(2)} \tag{IV-1}$$

denote the second reliability improvement option for subsystem (or pseudo-subsystem) i.

Since n(i) denotes the number of options available for subsystem i, n(i) = 0 when only the baseline subsystem i is available, i.e., no reliability improvement options for that subsystem. In this section, the only interest is in those subsystems for which n(i) > 0. Therefore, for each subsystem (or pseudo-subsystem) having reliability improvement options, the values of performance and cost

$$P_i^{(\ell)} \quad \text{and } C_i^{(\ell)} \qquad (\ell = 1, 2, \ldots, n(i)) \tag{IV-2}$$

define these options.

C. ADJUSTED BASELINE SYSTEM

Before applying the DSPC algorithm, it is necessary to determine if the Baseline System can be adjusted. <u>The adjustment of the Baseline System merely amounts to checking the options for each subsystem to determine if any of those options</u>

<u>yield higher or equal performance at lower cost or higher performance at equal cost</u>. If such an option exists, then that baseline subsystem is replaced by the lowest cost option. Although this can be done by inspection, the process will be described mathematically. As mentioned previously, such options could occur if, for instance, the subsystem designer discovers a means to reduce the unit cost of the subsystem or to improve the subsystem at either the same or a lower unit cost. (If life cycle cost is considered, the cost of improving subsystem reliability sometimes is more than compensated for by the resulting reduction in logistic support cost (Reference 3).) The simple procedure for adjusting the Baseline System (when possible) will now be described mathematically.

The first step is to enumerate the options in (IV-2) such that values of the subsystem performance options are ordered as follows:

$$P_i^{(o)} \leq P_i^{(1)} \leq P_i^{(2)} \leq \ldots \leq P_i^{(n(i))} \quad . \qquad \text{(IV-3)}$$

It is conceivable that one or more of the options (IV-2) has the property that for some value of $\ell > 0$

$$C_i^{(\ell)} \leq C_i^{(o)} \quad , \qquad \text{(IV-4)}$$

which means (because of the ordering (IV-3)) that better (or the same) subsystem performance is achievable at a lower or equal cost than the baseline subsystem.

For each subsystem having options with the property (IV-4), the baseline subsystem with

$$P_i^{(o)} \text{ and } C_i^{(o)}$$

should be replaced by that option for which $C_i^{(\ell)}$ is a minimum. If $\min_\ell \left\{ C_i^{(\ell)} \right\}$ occurs for more than one value of ℓ, then that option for which ℓ is a maximum should be selected since (because of the ordering (IV-3)) this provides the maximum performance at that cost. The test (IV-4) should be made for all subsystems for which options are available followed by adjustments of the Baseline System as required.

For example, suppose

$$C_i^{(2)} \leq C_i^{(o)} \quad , \tag{IV-5a}$$

and, in addition,

$$C_i^{(2)} = \min_{0 < \ell \leq n(i)} \left\{ C_i^{(\ell)} \right\} \quad . \tag{IV-5b}$$

Then subsystem i of the Baseline System should be replaced by its second option since the cost of Option 2 is the cheapest of all the options for subsystem i, and, because of the ordering (IV-3), the performance is greater than (or equal to) that of the baseline. From Expression (III-9) on page 30, the increased MCSP resulting from this adjustment becomes

$$P_{co} \left(\frac{P_i^{(2)}}{P_i^{(o)}} \right) \quad , \tag{IV-6a}$$

with a reduced system unit cost of

$$C_o - \left(C_i^{(o)} - C_i^{(2)} \right) \quad . \tag{IV-6b}$$

The Baseline MCSP and cost are adjusted stepwise in this manner for all subsystems for which condition (IV-4) holds. The general expression for calculating the MCSP and cost of the Adjusted Baseline System is as follows:

$$P_{c1} = P_{co} \prod_{i=1}^{N_s} \left(\frac{P_i^{(k(i))}}{P_i^{(o)}} \right) \tag{IV-7}$$

and

$$C_1 = C_o - \sum_{i=1}^{N_s} \left\{ C_i^{(o)} - C_i^{(k(i))} \right\} \quad , \tag{IV-8}$$

where N_s denotes the number of mission essential subsystems and $k(i)$ denotes the option selected in the adjustment of subsystem i. If $k(i) = 0$, then either subsystem i was unchanged in the baseline adjustment or subsystem i had no options. Notice that for these subsystems, the corresponding term in the product of Equation (IV-7) is 1, and in Equation (IV-8) the corresponding term in the sum is 0; hence, these subsystems have no effect on the calculation of P_{c1} or C_1. Therefore, only those subsystems for which $k(i) > 0$ have an effect on Equations (IV-7) and (IV-8).

After adjusting the original Baseline System (when possible), the DSPC algorithm can be applied.

D. DPSC CALCULATION PROCEDURE

Let P_{c1} and C_1 denote the MCSP and cost of the Adjusted Baseline System. This defines the first optimal vertex point of the DSPC curve. If the inequality (IV-4) was not satisfied for any subsystem, then no adjustment was made and

$$P_{c1} = P_{co} ,$$

$$C_1 = C_o . \tag{IV-9}$$

Since $k(i)$ was the option selected for subsystem i for the Adjusted Baseline System,

$$P_i^{(k(i))}$$

$$C_i^{(k(i))} \tag{IV-10}$$

are the new adjusted baseline values for subsystem i ($i = 1, 2, \ldots, N_s$). If $k(i) = 0$, then subsystem i was unchanged in the baseline adjustment. If $k(i) = n(i)$, then there are no remaining options for subsystem i. If $k(i) < n(i)$, then the remaining options for subsystem i are

$$P_i^{(\ell)} \text{ at cost } C_i^{(\ell)}, \quad \ell = (k(i) + 1), (k(i) + 2), \ldots, (n(i)) \quad . \qquad \text{(IV-11)}$$

The DSPC algorithm will now be applied to those subsystems having remaining options (IV-11), i.e., $k(i) < n(i)$.

The detailed mathematical proof of the DSPC optimization algorithm is documented in Reference 3. Only the step-by-step procedure for calculating the optimal vertex points of the DSPC curve will be described mathematically in the following few pages. Actually it is very simple to apply the DSPC methodology, although the mathematical notation necessary to describe the general procedure at first may appear complex. However, the simplicity of the procedure will be made clear by means of some detailed numerical examples in Section IV-E.

The first optimal vertex point of the DSPC curve corresponds to the Adjusted Baseline System or, if no adjustments were possible, to the original Baseline System. This first vertex point is the starting point for the DSPC optimization algorithm. The DSPC methodology will first be applied to determine the second vertex point, and then the general procedure for continuing the process will be described.

The option selected for subsystem i for the first vertex point is denoted by $k(i)$. If no adjustment was made for subsystem i, then $k(i) = 0$ (i.e., subsystem i remains at its baseline). For each subsystem having additional options (i.e., $k(i) < n(i)$), the DSPC procedure requires that a set of weighting factors be calculated for each such subsystem. These factors merely attach a value in substituting the present adjusted baseline option $k(i)$ for subsystem i by each of its remaining options $k(i) + 1, k(i) + 2, \ldots, n(i)$. It is necessary to evaluate the weights corresponding to the selection of each of the remaining options since the next option $(k(i) + 1)$ is not necessarily the best selection to be made next for subsystem i. In other words, it may be better to skip over one or more consecutive options. The optimal option to be selected next for subsystem i is determined by that option having the highest weight. The procedure for determining the second vertex point is as follows:

a. For those subsystems for which $k(i) < n(i)$, calculate for each of the remaining options for that subsystem ($\ell = k(i) + 1, k(i) + 2, \ldots, n(i)$) the weighting factors

$$\lambda_{i\ell} = \left(\frac{p_i^{(\ell)}}{p_i^{(k(i))}} \right)^{\gamma_{i\ell}} , \qquad \text{(IV-12a)}$$

where

$$\gamma_{i\ell} = \frac{1}{\Delta C_{i\ell}} \qquad \text{(IV-12b)}$$

and

$$\Delta C_{i\ell} = C_i^{(\ell)} - C_i^{(k(i))} . \qquad \text{(IV-12c)}$$

These values of $\lambda_{i\ell}$ attach a weight (value) in replacing the option $k(i)$ of the first vertex point by each of the remaining options for subsystem i (there are $n(i)-k(i)$ remaining options for subsystem i).

b. Considering only subsystem i, the optimal option to be selected next for that subsystem is determined by that value of ℓ (the option number) for which the weighting factor (IV-12a)is a maximum. Let the maximum weighting factor for subsystem i be denoted by $\lambda_i(2)$, i.e.,

$$\lambda_i(2) = \max_{k(i) < \ell \leq n(i)} \{\lambda_{i\ell}\} ; \qquad \text{(IV-13)}$$

and let $\ell(i, 2)$ denote that value of ℓ for which $\lambda_{i\ell}$ in (IV-13) is a maximum. The number 2 in the symbols $\lambda_i(2)$ and $\ell(i, 2)$ are used only to specify that the second vertex point is being calculated. The value $\lambda_i(2)$ attaches a weight to the optimal selection of the next option for subsystem i, and the corresponding value $\ell(i, 2)$ defines that optimal option with the highest weight. In other words

$$\lambda_i(2) = \lambda_{i\ell} \quad ,$$

where

$$\ell = \ell(i, 2) \quad .$$

c. The set of $\lambda_i(2)$ values together with the corresponding option $\ell(i, 2)$ was determined above for each subsystem having options remaining. The subsystem for which a different option is selected for the second vertex point is that subsystem having the maximum $\lambda_i(2)$ value $(i = 1, 2, \ldots, N_s)$. Let s(2) denote the subsystem selected where $\ell(s(2), 2)$ defines the optimal option for subsystem s(2). The optimal option $\ell(s(2), 2)$ for subsystem s(2) then replaces that option subsystem s(2) had at the first vertex point. This then defines the system configuration for the second vertex point. Only an option for one subsystem was changed in the process.

d. The MCSP and cost corresponding to the second vertex point are determined (as in Equation (IV-6)) by

$$P_{c2} = P_{c1}\left(\frac{P_i^{(\ell(i,\,2))}}{P_i^{(k(i))}}\right) \tag{IV-14a}$$

and

$$C_2 = C_1 + \Delta C_{i\ell(i,\,2)} = C_1 + \left(C_i^{(\ell(i,\,2)} - C_i^{(k(i))}\right) \tag{IV-14b}$$

where the value of i = s(2) to be substituted in Equations (IV-14a) and (IV-14b) was determined in step c above.

If, for instance,

$$\lambda_3(2) = \max\{\lambda_i(2)\} = \lambda_{32} \tag{IV-15}$$

then $\ell(3, 2) = 2$, and option 2 for subsystem 3 is selected for that vertex point following the Adjusted Baseline System; the other subsystems remain unchanged. In this case, the corresponding values of MCSP and cost for the second vertex point would be

$$P_{c2} = P_{c1}\left(\frac{P_3^{(2)}}{P_3^{(k(3))}}\right) , \tag{IV-16a}$$

and

$$C_2 = C_1 + \Delta C_{32} = C_1 + (C_3^{(2)} - C_3^{(k(3))}) . \tag{IV-16b}$$

To describe the general procedure, suppose the m-th vertex point has been determined. This means that, for that vertex point, the MCSP and cost are known as well as the associated optimal combination of subsystem options. These values were determined for $m = 2$ as described above. The procedure must now be continued to determine, in sequence, the vertex points 3, 4, 5, ..., etc. The procedure for determining the next (i.e., the $(m + 1)$-st) vertex point is as follows:

a. The subsystem replaced in defining the configuration for the m-th vertex point was determined by selecting that subsystem which yielded the maximum of a set of weighting factors $\{\lambda_i(m)\}$. Let $s(m)$ denote that subsystem selected for the m-th vertex point, and let $\ell(s(m), m)$ denote the optimal option selected for that subsystem. To determine the $(m + 1)$-st vertex point, a new set of weighting factors must be determined. The only subsystem changed in going from the $(m - 1)$-st to the m-th vertex point was subsystem $s(m)$. Therefore, the only change in the set of weighting factors $\{\lambda_i(m + 1)\}$ required to determine the $(m + 1)$-st vertex point is that weighting factor corresponding to subsystem $s(m)$. The new weighting factor for subsystem $s(m)$ is determined as follows:

(1) If $\ell(s(m), m) = n(s(m))$, then there are no options remaining for subsystem $s(m)$, and $\lambda_{s(m)}(m + 1)$ is set equal to 0.

(2) If $\ell(s(m), m) < n(s(m))$, then there are options remaining for subsystem $s(m)$. In a manner analogous to the procedure described for determining the second vertex point, a set of weighting factors for subsystem $s(m)$ is calculated for the remaining options $\ell = \ell(s(m), m) + 1, \ell(s(m), m) + 2, \ldots, n(s(m))$ by setting

$$i = s(m)$$

$$k(i) = \ell(s(m), m) \tag{IV-17}$$

in Equation (IV-12). The new weighting factor $\lambda_{s(m)}(m + 1)$ for subsystem $s(m)$ (required to determine the $(m + 1)$-st vertex point) is determined by the maximum of the weighting factors for subsystem $s(m)$ calculated above, where $\ell(s(m), m + 1)$ denotes the corresponding optimal option for that subsystem. Thus, the new weighting factor for subsystem $s(m)$ is determined as well as the next optimal option $\ell(s(m), m + 1)$ for that subsystem. For the other subsystems, no change is made, i.e., for $i \neq s(m)$

$$\lambda_i(m + 1) = \lambda_i(m)$$

$$\ell(i, m + 1) = \ell(i, m) \quad . \tag{IV-18}$$

Therefore, the new set

$$\{\lambda_i(m + 1)\} \tag{IV-19a}$$

and the corresponding set of optimal options

$$\{\ell(i, m + 1)\} \tag{IV-19b}$$

are known, and the $(m + 1)$-st vertex point can now be determined. Only one member (for $i = s(m)$) in the set (IV-19a) and in the set (IV-19b) is different from the sets $\{\lambda_i(m)\}$ and $\{\ell(i, m)\}$.

b. The subsystem to be selected for the (m + 1)-st vertex point is determined by that value of i for which $\lambda_i(m + 1)$ in (IV-19a) is a maximum. Letting s(m + 1) denote this subsystem, the (m + 1)-st vertex point is determined by selecting option $\ell(s(m + 1), m + 1)$ for subsystem s(m + 1).

c. The MCSP and cost corresponding to the (m + 1)-st vertex point are determined by

$$P_{c(m + 1)} = P_{cm}\left(\frac{P_i^{(\ell)}}{P_i^{(k)}}\right) \qquad \text{(IV-20a)}$$

and

$$C_{(m + 1)} = C_m + \Delta C_{s(m + 1)\ell} = C_m + \left(C^{(\ell)}_{s(m + 1)} - C^{(k)}_{s(m + 1)}\right) \qquad \text{(IV-20b)}$$

where

$$\ell = \ell(s(m + 1), m + 1) \qquad \text{(IV-20c)}$$

and

$$k = \ell(s(m + 1), m) \qquad \text{(IV-20d)}$$

The value of k is the option for subsystem s(m + 1) which it had at the m-th vertex point.

d. The process is continued until no options remain for any subsystem. In other words, the above process is applied for m = 2 to determine the third vertex point, then m is set equal to 3, 4, 5, ... to determine the remaining vertex points.

In summary, the step-by-step procedure for implementing the DSPC methodology can be described briefly as follows:

1. Determine the MCSP of the Baseline System (Section III-C) and the unit cost C_o.

2. For each subsystem with options, order the performance values (Expression (IV-3)).

3. Adjust the Baseline System if possible (test IV-4). This defines the first optimal vertex point; the MCSP and cost are determined by Equations (IV-7) and (IV-8).

4. Calculate the set of weighting factors and optimal options (for determining the second vertex point) as described on pages 56 to 59. This determines the second vertex point where the corresponding values of MCSP and cost are calculated by Equations (IV-14a) and (IV-14b).

5. Determine, in sequence, the remaining vertex points 3, 4, ..., etc. as described on pages 59 and 50. (In going from one vertex point to the next, only one weighting factor is changed.)

It is important to outline the procedure to be followed in determining the new DSPC curve when an additional option becomes available for some subsystem. Suppose an additional option becomes available for subsystem i; this means that subsystem i then has $n(i) + 1$ options. The first step is to order the performance values for that subsystem (step 2), and then repeat steps 3, 4, and 5. This process requires at most the calculation of $n(i) + 1$ new weighting factors for subsystem i; the weighting factors for all other subsystems remain the same. Therefore, the new DSPC curve can be determined very quickly.

An interesting comment that can be made at this point is that the optimal selection of subsystem options is independent of the system MCSP. From Equations (IV-12) it is clear that the weight attached to the selection of a subsystem option is dependent only upon the relative improvement of the particular subsystems and their associated cost.

E. DSPC EXAMPLES

1. Simplified Example. To clarify the step-by-step DSPC procedure described above, the methodology first will be applied in detail to a simple hypothetical numerical example. Suppose a system consists of only 3 essential subsystems where the baseline values of performance and cost (in $ thousands) of the subsystems are presented in Table 7.

Table 7

BASELINE SYSTEM

SUBSYSTEM	$P_i^{(o)}$	$C_i^{(o)}$
1	.9418	24.6
2	.9048	19.0
3	.8187	33.5

The first step is to calculate the MCSP and cost of the Baseline System:

$$P_{co} = \prod_{i=1}^{3} P_i^{(o)} = (.9418)\ (.9048)\ (.8187) = .6976 \qquad \text{(IV-21a)}$$

and

$$C_o = \sum_{i=1}^{3} C_i^{(o)} = 24.6 + 19.0 + 33.5 = \$77.1 \qquad \text{(IV-21b)}$$

If there are other costs associated with the Baseline System (e.g., overhead cost, etc.), these are merely added to the cost determined by (IV-21b).

Suppose 2 options become available for each subsystem where the options are defined in Table 8.

Table 8

SUBSYSTEM OPTIONS

SUBSYSTEM	PERFORMANCE	UNIT COST
1	.9802 .9632	24.0 19.5
2	.9512 .9802	20.0 21.2
3	.9299 .8752	44.6 35.0

The second step is to order the options for each subsystem by increasing performance (Expression (IV-3)). This then leads to Table 9 which displays the baseline values of each subsystem and the proper ordering of the options.

Table 9

COST AND MISSION PERFORMANCE OF SUBSYSTEM OPTIONS

SUBSYSTEM NUMBER i	BASELINE		OPTION 1		OPTION 2	
	$P_i^{(o)}$	$C_i^{(o)}$	$P_i^{(1)}$	$C_i^{(1)}$	$P_i^{(2)}$	$C_i^{(2)}$
1	.9418	24.6	.9632	19.5	.9802	24.0
2	.9048	19.0	.9512	20.0	.9802	21.2
3	.8187	33.5	.8752	35.0	.9299	44.6

The third step is to determine if the Baseline System can be adjusted (i.e., perform the test (IV-4)). By inspection, Option 1 for subsystem 1 should replace the baseline subsystem 1 since that option has higher performance at a lower cost. This is the only adjustment possible. Thus, the Adjusted Baseline System (the first optimal vertex point) consists of

Option 1 for Subsystem 1,
Baseline for Subsystem 2,
Baseline for Subsystem 3 .

The corresponding MCSP and cost of the Adjusted Baseline System are

$$P_{c1} = P_{co}\left(\frac{P_1^{(1)}}{P_1^{(o)}}\right) = .6976\left(\frac{.9632}{.9418}\right) = .7135 \qquad \text{(IV-22a)}$$

and

$$C_1 = C_o + (C_1^{(1)} - C_1^{(o)}) = 77.1 + (19.5 - 24.6) = \$72.0 \ . \qquad \text{(IV-22b)}$$

These results show the improvement in MCSP at a reduced cost resulting from the adjustment of the Baseline System. The DSPC calculations will now be made in a step-by-step fashion to determine the subsequent optimal vertex points of the MCSP versus cost curve. As mentioned previously, the methodology does not require the evaluation of every conceivable combination of options which on a complex system would require a time consuming and prohibitively costly computer analysis. The methodology allows a program engineer to quickly screen the options using an electronic calculator to select only those options whose cost/performance index justifies further consideration.

The fourth step is to determine the second vertex point. This is the beginning of the DSPC algorithm; therefore, the calculations of the $\lambda_{i\ell}$ values defined by Equations (IV-12) must be made. Since Option 1 for subsystem 1 was selected for the Adjusted Baseline System k(1) = 1, whereas k(2) = k(3) = 0 since no adjustment was possible for these subsystems. Application of Equation (IV-12) yields the set:

$$\lambda_{12} = \left(\frac{P_1^{(2)}}{P_1^{(1)}}\right)^{\frac{1}{\Delta C_{12}}} = \left(\frac{.9802}{.9632}\right)^{\frac{1}{4.5}} = 1.0039;$$

$$\lambda_{21} = \left(\frac{P_2^{(1)}}{P_2^{(o)}}\right)^{\frac{1}{\Delta C_{21}}} = \left(\frac{.9512}{.9048}\right)^{\frac{1}{1}} = 1.0513,$$

$$\lambda_{22} = \left(\frac{P_2^{(2)}}{P_2^{(o)}}\right)^{\frac{1}{\Delta C_{22}}} = \left(\frac{.9802}{.9048}\right)^{\frac{1}{2.2}} = 1.0371;$$

$$\lambda_{31} = \left(\frac{P_3^{(1)}}{P_3^{(o)}}\right)^{\frac{1}{\Delta C_{31}}} = \left(\frac{.8752}{.8187}\right)^{\frac{1}{1.5}} = 1.0455,$$

$$\lambda_{32} = \left(\frac{P_3^{(2)}}{P_3^{(o)}}\right)^{\frac{1}{\Delta C_{32}}} = \left(\frac{.9299}{.8187}\right)^{\frac{1}{11.1}} = 1.0115 \quad . \qquad \text{(IV-23)}$$

Therefore, (from Equation (IV-13)) taking the maximum value of $\lambda_{i\ell}$ for subsystems $i = 1, 2, 3$ yields

$$\lambda_1(2) = \lambda_{12} = 1.0039,$$

$$\lambda_2(2) = \lambda_{21} = 1.0513,$$

$$\lambda_3(2) = \lambda_{31} = 1.0455 \quad . \qquad \text{(IV-24)}$$

Thus, the only remaining option for subsystem 1 (which already is at Option 1) is Option 2 with weighting factor λ_{12}, for subsystem 2 Option 1 is the next optimal option, and Option 1 for subsystem 3. The maximum of the set (IV-24) is

$$\lambda_2(2) = \lambda_{21} \quad . \qquad \text{(IV-25)}$$

Therefore, for the second vertex point the baseline subsystem 2 should be replaced by Option 1 (indicated by the second subscript of λ_{21}). The system configuration for the second vertex point consists of

Option 1 for subsystem 1,
Option 1 for subsystem 2,
Baseline subsystem 3.

The corresponding MCSP and cost are

$$P_{c2} = P_{c1}\left(\frac{P_2^{(1)}}{P_2^{(o)}}\right) = .7135\left(\frac{.9512}{.9048}\right) = .7501 \qquad \text{(IV-26a)}$$

and

$$C_2 = C_1 + (C_2^{(1)} - C_2^{(o)}) = 72.0 + (20.0 - 19.0) = \$73.0 \quad . \qquad \text{(IV-26b)}$$

The determination of the second vertex point is the most time consuming step since weighting factors for all subsystems had to be calculated. However, to determine, in sequence, the remaining vertex points the weighting factor of only one subsystem is changed in proceeding from one vertex point to the next.

The fifth step is to determine, in sequence, the remaining vertex points 3, 4, ... This procedure is described starting on page 59. To calculate the third vertex point set $m = 2$; since Option 1 for subsystem 2 was selected for the second vertex point $s(2) = 2$ (subsystem selected) and $\ell(2, 2) = 1$ (option selected) Therefore, the only weighting factor to be changed is that for subsystem 2. Since only one more option remains for subsystem 2, the new weighting factor for subsystem 2 is

$$\lambda_2(3) = \lambda_{22} = \left(\frac{P_2^{(2)}}{P_2^{(1)}}\right)^{\frac{1}{\Delta C_{22}}} = \left(\frac{.9802}{.9512}\right)^{\frac{1}{1.2}} = 1.0253 \qquad \text{(IV-27)}$$

and $\ell(2, 3) = 2$. Therefore, for determining the third vertex point, the new set (with only $\lambda_2(3)$ changed) of weighting factors becomes (using (IV-27) and (IV-24))

$$\lambda_1(3) = \lambda_{12} = 1.0039,$$

$$\lambda_2(3) = \lambda_{22} = 1.0253,$$

$$\lambda_3(3) = \lambda_{31} = 1.0455 \quad . \qquad \text{(IV-28)}$$

From the set (IV-28), $\lambda_3(3) = \lambda_{31}$ is the maximum, and therefore Option 1 for subsystem 3 is selected. The system configuration for the third vertex point is therefore

Option 1 for subsystem 1,
Option 1 for subsystem 2,
Option 1 for subsystem 3 .

The MCSP and cost for the third vertex point are

$$P_{c3} = P_{c2}\left(\frac{P_3^{(1)}}{P_3^{(o)}}\right) = .7501\left(\frac{.8752}{.8187}\right) = .8019 \qquad \text{(IV-29a)}$$

and

$$C_3 = C_2 + (C_3^{(1)} - C_3^{(o)}) = 73.0 + (1.5) = \$74.5 \quad . \qquad \text{(IV-29b)}$$

To determine the fourth vertex point set $m = 3$ and $s(3) = 3$ (since subsystem 3 was changed in the previous step) and $\ell(3, 3) = 1$ (since Option 1 was selected for subsystem 3). The new weighting factor to be calculated for subsystem 3 is

$$\lambda_3(4) = \lambda_{32} = \left(\frac{P_3^{(2)}}{P_3^{(1)}}\right)^{\frac{1}{\Delta C_{31}}} = \left(\frac{.9299}{.8752}\right)^{\frac{1}{9.6}} = 1.0063 \quad . \qquad \text{(IV-30)}$$

Therefore, the new set of weights required to determine the fourth vertex point is

$$\lambda_1(4) = \lambda_{12} = 1.0039,$$

$$\lambda_2(4) = \lambda_{22} = 1.0253,$$

$$\lambda_3(4) = \lambda_{32} = 1.0063 \quad . \qquad \text{(IV-31)}$$

From the set (IV-31), $\lambda_2(4) = \lambda_{22}$ is the maximum, and therefore Option 2 for subsystem 2 is selected. The system configuration for the fourth vertex point is:

Option 1 for subsystem 1,
Option 2 for subsystem 2,
Option 1 for subsystem 3.

The MCSP and cost for the fourth vertex point are

$$P_{c4} = P_{c3}\left(\frac{P_2^{(2)}}{P_2^{(1)}}\right) = .8019\left(\frac{.9802}{.9512}\right) = .8263 \qquad \text{(IV-32a)}$$

and

$$C_4 = C_3 + (C_2^{(2)} - C_2^{(1)}) = 74.5 + (1.2) = \$75.7 \quad . \qquad \text{(IV-32b)}$$

Since there are no remaining options for subsystem 2, $\lambda_2(5) = 0$; and the new set of weighting factors for determining the fifth vertex point becomes

$$\lambda_1(5) = \lambda_{12} = 1.0039,$$

$$\lambda_2(5) = 0,$$

$$\lambda_3(5) = \lambda_{32} = 1.0063 \quad . \qquad \text{(IV-33)}$$

From the set (IV-33), it follows that Option 2 for subsystem 3 should be selected. The system configuration for the fifth vertex point is therefore

Option 1 for subsystem 1,
Option 2 for subsystem 2,
Option 2 for subsystem 3.

The MCSP and cost for the fifth vertex point are

$$P_{c5} = P_{c4}\left(\frac{P_3^{(2)}}{P_3^{(1)}}\right) = .8263\left(\frac{.9299}{.8752}\right) = .8779 \qquad \text{(IV-34a)}$$

and

$$C_5 = C_4 + (C_3^{(2)} - C_3^{(1)}) = 75.7 + (9.6) = \$85.3 \quad . \qquad \text{(IV-34b)}$$

No options remain for subsystem 3. Therefore, $\lambda_3(6) = 0$ and the new set of weighting factors is

$$\lambda_1(6) = \lambda_{12} = 1.0039,$$

$$\lambda_2(6) = 0,$$

$$\lambda_3(6) = 0 \quad . \qquad \text{(IV-35)}$$

Therefore, the only remaining selection is Option 2 for subsystem 1, and

$$P_{c6} = P_{c5}\left(\frac{P_1^{(2)}}{P_1^{(1)}}\right) = .8779\left(\frac{.9802}{.9632}\right) = .8934 \qquad \text{(IV-36a)}$$

and

$$C_6 = C_5 + (C_1^{(2)} - C_1^{(1)}) = 85.3 + (4.5) = \$89.8 \quad . \qquad \text{(IV-36b)}$$

Table 10 lists the configurations together with the corresponding values of MCSP and cost as determined for the above example by means of the DSPC model.

Table 10

MCSP AND COST RESULTS

VERTEX POINT	COMBINATION OF OPTIONS			MCSP	UNIT COST (Thousands)
	SUBSYSTEM 1	SUBSYSTEM 2	SUBSYSTEM 3		
0 (Baseline)	0	0	0	.6976	77.1
1	1	0	0	.7135	72.0
2	1	1	0	.7501	73.0
3	1	1	1	.8019	74.5
4	1	2	1	.8263	75.7
5	1	2	2	.8779	85.3
6	2	2	2	.8934	89.8

The DSPC curve is shown in Figure 9 which shows that only 6 of the 27 possible configurations are optimal. For this simple example, the remaining 21 nonoptimal values were calculated and are shown in the figure.

2. <u>Redundancy Options</u>. Redundancy is perhaps the most straightforward reliability improvement technique to consider for a subsystem option when volume, weight, and other constraints are met. Furthermore, the probability of success is easily calculated according to well-defined rules, and the cost is a simple sum of the costs of the individual elements. However, even when volume and weight constraints allow redundancy of certain subsystems, these options are not necessarily optimal as the following example will show. The DSPC procedure will be applied to a hypothetical example in which one subsystem can be made redundant. Implementation of the DSPC model will then determine whether the redundancy option should be selected, and, if so, at what vertex point on the DSPC curve.

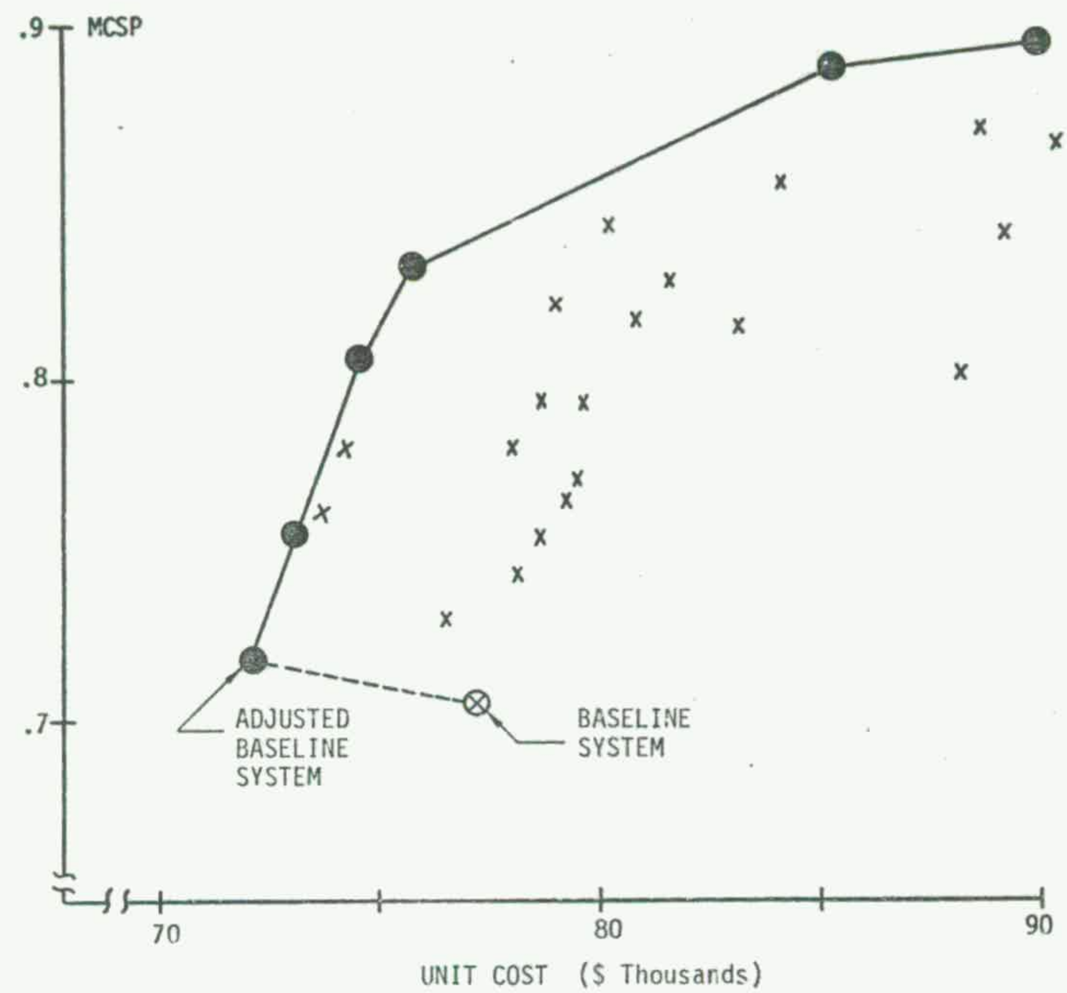


Figure 9. DSPC Example.

Consider a system consisting of three essential subsystems, with the performance and unit cost ($ in thousands) values of the options listed in Table 11.

Table 11

SUBSYSTEM COST AND PERFORMANCE VALUES

SUBSYSTEM NUMBER i	BASELINE		OPTION 1		OPTION 2	
	$P_i^{(o)}$	$C_i^{(o)}$	$P_i^{(1)}$	$C_i^{(1)}$	$P_i^{(2)}$	$C_i^{(2)}$
1	.88	35	.92	39	.98	56
2	.85	30	.90	35	.97	41
3	.76	20	---	--	---	--

Suppose space, weight, and other constraints allow subsystem 3 to be redundant (operative redundancy). This then represents an option for subsystem 3 where $P_3^{(1)}$ and $C_3^{(1)}$ are calculated as follows:

$$P_3^{(1)} = 1 - \left(1 - P_3^{(o)}\right)^2 = 1 - (1 - .76)^2 = .94 \qquad \text{(IV-37a)}$$

$$C_3^{(1)} = 2\, C_3^{(o)} = \$40 \quad . \qquad \text{(IV-37b)}$$

Inserting the values (IV-37a) and (IV-37b) into Table 11 for the redundancy Option 1 for subsystem 3, yields Table 12. The ordering of the options by increasing performance (Expression (IV-3)) has already been performed.

Table 12

SUBSYSTEM VALUES WITH REDUNDANCY OPTION

SUBSYSTEM NUMBER i	BASELINE		OPTION 1		OPTION 2	
	$P_i^{(o)}$	$C_i^{(o)}$	$P_i^{(1)}$	$C_i^{(1)}$	$P_i^{(2)}$	$C_i^{(2)}$
1	.88	35	.92	39	.98	56
2	.85	30	.90	35	.97	41
3	.76	20	.94	40	---	--

Applying the test (IV-4) shows that the Baseline System cannot be adjusted. Therefore, the first optimal vertex point corresponds to the Baseline System with the MCSP and cost calculated as follows:

$$P_{c1} = P_{co} = \prod_{i=1}^{3} P_i^{(o)} = (.88)(.85)(.76) = .57 \qquad \text{(IV-38a)}$$

and

$$C_1 = C_o = \sum_{i=1}^{3} C_i^{(o)} = 35 + 30 + 20 = \$85 \quad . \qquad \text{(IV-38b)}$$

To determine the second vertex point, the set of weighting values $\lambda_{i\ell}$ defined by Equations (IV-12) must be calculated. The Baseline System could not be adjusted and therefore, $k(1) = k(2) = k(3) = 0$. Applying Equation (IV-12) to each subsystem to determine the weight in going from its baseline value to each of its options yields the set:

$$\lambda_{11} = \left(\frac{P_1^{(1)}}{P_1^{(o)}}\right)^{\frac{1}{\Delta C_{11}}} = \left(\frac{.92}{.88}\right)^{\frac{1}{4}} = 1.0112 \quad ,$$

$$\lambda_{12} = \left(\frac{P_1^{(2)}}{P_1^{(o)}}\right)^{\frac{1}{\Delta C_{12}}} = \left(\frac{.98}{.88}\right)^{\frac{1}{21}} = 1.0051 \quad ;$$

$$\lambda_{21} = \left(\frac{P_2^{(1)}}{P_2^{(o)}}\right)^{\frac{1}{\Delta C_{21}}} = \left(\frac{.90}{.85}\right)^{\frac{1}{5}} = 1.0115 \quad ,$$

$$\lambda_{22} = \left(\frac{P_2^{(2)}}{P_2^{(o)}}\right)^{\frac{1}{\Delta C_{22}}} = \left(\frac{.97}{.85}\right)^{\frac{1}{11}} = 1.0121 \quad ;$$

$$\lambda_{31} = \left(\frac{P_3^{(1)}}{P_3^{(o)}}\right)^{\frac{1}{\Delta C_{31}}} = \left(\frac{.94}{.76}\right)^{\frac{1}{20}} = 1.0107 \quad . \qquad \text{(IV-39)}$$

From the set (IV-39), the next optimal option for subsystem 1 is Option 1, for subsystem 2 Option 1 is rejected since Option 2 has a higher weight, and for subsystem 3 the only option is the redundancy Option 1. Therefore, taking the maximum value of $\lambda_{i\ell}$ for subsystems i = 1, 2, 3 yields the set:

$$\lambda_1(2) = \lambda_{11} = 1.0112,$$

$$\lambda_2(2) = \lambda_{22} = 1.0121,$$

$$\lambda_3(2) = \lambda_{31} = 1.0107 \quad . \qquad \text{(IV-40)}$$

Since the maximum of the set of weights (IV-40) is $\lambda_2(2) = \lambda_{22}$, the next optimal option is Option 2 for subsystem 2. Therefore, for the second vertex point, the baseline subsystem 2 should be replaced by Option 2. The system configuration for the second vertex point is

Baseline for subsystem 1,
Option 2 for subsystem 2,
Baseline for subsystem 3 .

The corresponding MCSP and cost of the second vertex point are

$$P_{c2} = P_{c1}\left(\frac{P_2^{(2)}}{P_2^{(o)}}\right) = .57\left(\frac{.97}{.85}\right) = .65 \qquad \text{(IV-41a)}$$

and

$$C_2 = C_1 + \left(C_2^{(2)} - C_2^{(o)}\right) = 85 + (41 - 30) = \$96 \quad . \qquad \text{(IV-41b)}$$

Since no additional options remain for subsystem 2, $\lambda_2(3) = 0$ while $\lambda_1(3) = \lambda_1(2)$ and $\lambda_3(3) = \lambda_3(2)$. Thus, the new set of λ values is

$$\lambda_1(3) = \lambda_{11} = 1.0112,$$

$$\lambda_2(3) = 0,$$

$$\lambda_3(3) = \lambda_{31} = 1.0107 \quad . \tag{IV-42}$$

From (IV-42), it follows that Option 1 for subsystem 1 should be selected, and the system configuration for the third vertex point consists of

Option 1 for subsystem 1,
Option 2 for subsystem 2,
Baseline for subsystem 3 .

The corresponding MCSP and cost of the third vertex point are

$$P_{c3} = P_{c2}\left(\frac{P_1^{(1)}}{P_1^{(o)}}\right) = .65\left(\frac{.92}{.88}\right) = .68 \tag{IV-43a}$$

and

$$C_3 = C_2 + \left(C_2^{(1)} - C_2^{(o)}\right) = 96 + (39 - 35) = \$100 \quad . \tag{IV-43b}$$

To determine the fourth vertex point set m = 3 and s(3) = 1 since subsystem 1 was changed in determining the third vertex point. In addition, $\ell(1, 3) = 1$ since Option 1 was selected for subsystem 1. The new weighting factor for subsystem 1 is then (since only Option 2 remains for subsystem 1)

$$\lambda_1(4) = \lambda_{12} = \left(\frac{P_1^{(2)}}{P_1^{(1)}}\right)^{\frac{1}{\Delta C_{12}}} = \left(\frac{.98}{.92}\right)^{\frac{1}{17}} = 1.0037 \quad . \tag{IV-44}$$

Therefore, the new set of weights required to determine the fourth vertex point is

$$\lambda_1(4) = \lambda_{12} = 1.0037,$$

$$\lambda_2(4) = 0,$$

$$\lambda_3(4) = \lambda_{31} = 1.0107 \quad . \qquad \text{(IV-45)}$$

The maximum of the values (IV-45) is λ_{31} which means that Option 1 (redundancy option) for subsystem 3 should now be selected. The system configuration for the fourth vertex point is therefore

Option 1 for subsystem 1,
Option 2 for subsystem 2,
Option 1 for subsystem 3 .

The MCSP and cost for the fourth vertex point are

$$P_{c4} = P_{c3}\left(\frac{P_3^{(1)}}{P_3^{(o)}}\right) = .68\left(\frac{.94}{.76}\right) = .84 \qquad \text{(IV-46a)}$$

and

$$C_4 = C_3 + \left(C_3^{(1)} - C_3^{(o)}\right) = 100 + (40-20) = \$120 \quad . \qquad \text{(IV-46b)}$$

Since no additional options exist for subsystem 3, $\lambda_3(5) = 0$. The new set of weights becomes

$$\lambda_1(5) = \lambda_{12} = 1.0037,$$

$$\lambda_2(5) = 0,$$

$$\lambda_3(5) = 0 \quad . \qquad \text{(IV-47)}$$

From (IV-47), it follows that the only remaining option is Option 2 for subsystem 1, and the system configuration for the fifth and last vertex point consists of

Option 2 for subsystem 1,
Option 2 for subsystem 2,
Option 1 for subsystem 3 .

The MCSP and cost of the fifth vertex point are

$$P_{c5} = P_{c4}\left(\frac{P_1^{(2)}}{P_1^{(1)}}\right) = .84\left(\frac{.98}{.92}\right) = .89 \tag{IV-48a}$$

and

$$C_5 = C_4 + \left(C_1^{(2)} - C_1^{(1)}\right) = 120 + (17) = \$137 \quad . \tag{IV-48b}$$

Table 13 lists the configurations together with the corresponding values of MCSP and cost. Observe that the redundancy option was not selected until the fourth vertex point. This points out the fact that even if subsystem redundancy is possible, it does not necessarily mean that it should be selected. It is dependent upon performance and cost.

Table 13

MCSP AND COST RESULTS FOR REDUNDANCY EXAMPLE

VERTEX POINT	COMBINATION OF OPTIONS			MCSP	UNIT COST (Thousands)
	SUBSYSTEM 1	SUBSYSTEM 2	SUBSYSTEM 3		
1	0	0	0	.57	85
2	0	2	0	.65	96
3	1	2	0	.68	100
4	1	2	1	.84	120
5	2	2	1	.89	137

3. <u>Target Activated Munitions</u>. In Section III-E-1, a hypothetical mine example was introduced, and its Baseline System is defined in Table 1 on page 33. The MCSP of this Baseline System was calculated to be .25. Suppose that options become available for 5 of the mine subsystems with no options for the remaining subsystems. These options are defined in Table 14, where the ordering of the options (Expression IV-3) has already been performed. It is assumed that the unit cost of the Baseline System is $200.00. Therefore, for the Baseline System

$$P_{co} = .25 \qquad \text{(IV-49a)}$$

and

$$C_o = \$200.00 \quad . \qquad \text{(IV-49b)}$$

Table 14

SUBSYSTEM OPTIONS FOR MINE

SUBSYSTEM	BASELINE		OPTION 1		OPTION 2		OPTION 3	
	$P_i^{(o)}$	$C_i^{(o)}$	$P_i^{(1)}$	$C_i^{(1)}$	$P_i^{(2)}$	$C_i^{(2)}$	$P_i^{(3)}$	$C_i^{(3)}$
1. Fin	.70	1.00	.75	1.50	.85	1.75	.99	2.75
2. Brake	.75	2.50	.85	3.00	.97	4.50	---	----
3. Cutter	.80	3.00	.90	2.50	.98	5.00	---	----
4. Body	.88	5.00	.95	7.00	.99	9.00	---	----
5. Safe & Arm	.90	4.00	.97	5.50	.99	7.50	---	----

By inspection of Table 14, it is clear that the Baseline System can be adjusted by replacing the Cutter (subsystem 3) by Option 1, since this option has higher performance at lower cost. Therefore, since no other adjustments are possible, the Adjusted Baseline System (the first optimal vertex point) consists of

Baseline for subsystem 1,
Baseline for subsystem 2,
Option 1 for subsystem 3,
Baseline for subsystem 4,
Baseline for subsystem 5 .

The MCSP and cost of the Adjusted Baseline System are

$$P_{c1} = P_{co}\left(\frac{P_3^{(1)}}{P_3^{(o)}}\right) = .25\left(\frac{.90}{.80}\right) = .28 \qquad \text{(IV-50a)}$$

and

$$C_1 = C_o + \left(C_3^{(1)} - C_3^{(o)}\right) = 200 + (2.50 - 3.00) = \$199.50 \ . \qquad \text{(IV-50b)}$$

The DSPC model can now be applied to determine, step-by-step, the remaining optimal vertex points. To determine the second vertex point, the set of weighting factors $\lambda_{i\ell}$ defined by Equations (IV-12) must be calculated for the remaining options of each subsystem (i = 1, 2, 3, 4, 5). This is the most time consuming step. Since for the Adjusted Baseline System Option 1 was selected for subsystem 3, k(3) = 1 whereas k(1) = k(2) = k(4) = k(5) = 0. Application of Equation (IV-12) yields for subsystem 1 the following set of weights in going from its present baseline value to each of the remaining options:

$$\lambda_{11} = \left(\frac{.75}{.70}\right)^{\frac{1}{.50}} \simeq 1.1480 \ , \quad \lambda_{12} = \left(\frac{.85}{.70}\right)^{\frac{1}{.75}} = 1.2955 \ ,$$

$$\lambda_{13} = \left(\frac{.99}{.70}\right)^{\frac{1}{1.75}} = 1.2190 \ . \qquad \text{(IV-51)}$$

Therefore, since the maximum of the set is λ_{12}, the next optimal option for subsystem 1 is Option 2 with weight

$$\lambda_1(2) = \lambda_{12} = 1.2955 \qquad \text{(IV-52)}$$

which means that Option 1 was rejected. For subsystem 2, the option weights are

$$\lambda_{21} = \left(\frac{.85}{.75}\right)^{\frac{1}{.50}} = 1.2844 \quad , \quad \lambda_{22} = \left(\frac{.97}{.75}\right)^{\frac{1}{2.00}} = 1.1372 \quad . \qquad \text{(IV-53)}$$

Therefore, the next optimal option for subsystem 2 is Option 1 with weight

$$\lambda_2(2) = \lambda_{21} = 1.2844 \quad . \qquad \text{(IV-54)}$$

For subsystem 3, k(3) = 1 which means that the only remaining weight is

$$\lambda_{32} = \left(\frac{.98}{.90}\right)^{\frac{1}{2.50}} = 1.0346 \quad . \qquad \text{(IV-55)}$$

Therefore,

$$\lambda_3(2) = \lambda_{32} = 1.0346 \quad . \qquad \text{(IV-56)}$$

For subsystem 4, the option weights are

$$\lambda_{41} = \left(\frac{.95}{.88}\right)^{\frac{1}{2.00}} = 1.0390 \quad , \quad \lambda_{42} = \left(\frac{.99}{.88}\right)^{\frac{1}{4.00}} = 1.0299 \quad . \qquad \text{(IV-57)}$$

Therefore,

$$\lambda_4(2) = \lambda_{41} = 1.0390 \quad . \qquad \text{(IV-58)}$$

For subsystem 5, the option weights are

$$\lambda_{51} = \left(\frac{.97}{.90}\right)^{\frac{1}{1.50}} = 1.0512 \quad , \quad \lambda_{52} = \left(\frac{.99}{.90}\right)^{\frac{1}{3.50}} = 1.0276 \quad . \qquad \text{(IV-59)}$$

Therefore,

$$\lambda_5(2) = \lambda_{51} = 1.0512 \quad . \tag{IV-60}$$

The values (IV-52), (IV-54), (IV-56), (IV-58), and (IV-60) required to determine the second vertex point are

$$\lambda_1(2) = \lambda_{12} = 1.2955,$$

$$\lambda_2(2) = \lambda_{21} = 1.2844,$$

$$\lambda_3(2) = \lambda_{32} = 1.0346,$$

$$\lambda_4(2) = \lambda_{41} = 1.0390,$$

$$\lambda_5(2) = \lambda_{51} = 1.0512 \quad . \tag{IV-61}$$

The maximum of the set (IV-61) is λ_{12}; therefore, the baseline subsystem 1 should be replaced by Option 2. Therefore, the second vertex point is defined by the system configuration

Option 2 for subsystem 1,
Baseline for subsystem 2,
Option 1 for subsystem 3,
Baseline for subsystem 4,
Baseline for subsystem 5 .

The MCSP and cost of the second vertex point are

$$P_{c2} = P_{c1}\left(\frac{P_1^{(2)}}{P_1^{(o)}}\right) = .28 \left(\frac{.85}{.70}\right) = .34 \tag{IV-62a}$$

and

$$C_2 = C_1 + \left(C_1^{(2)} - C_1^{(o)}\right) = 199.50 + (1.75 - 1.00) = \$200.25 \quad . \text{(IV-62b)}$$

To calculate the third vertex point m = 2, and since Option 2 was selected for subsystem 1 for the second vertex point $s(2) = 1$ and $\ell(2, 2) = 1$. Only one more option remains for subsystem 1, and therefore

$$\lambda_1(3) = \lambda_{13} = \left(\frac{P_1^{(3)}}{P_1^{(2)}}\right)^{\frac{1}{\Delta C_{13}}} = \left(\frac{.99}{.85}\right)^{\frac{1}{1.00}} = 1.1647 \qquad \text{(IV-63)}$$

and $\ell(1, 3) = 3$. The corresponding weighting factors for the other subsystems remain unchanged (IV-61). Therefore, for determining the third vertex point the required set of weighting factors is

$$\lambda_1(3) = \lambda_{13} = 1.1647,$$

$$\lambda_2(3) = \lambda_{21} = 1.2844,$$

$$\lambda_3(3) = \lambda_{32} = 1.0346,$$

$$\lambda_4(3) = \lambda_{41} = 1.0390,$$

$$\lambda_5(3) = \lambda_{51} = 1.0512 \quad . \qquad \text{(IV-64)}$$

The maximum of the set (IV-64) is λ_{21} which means that Option 1 for subsystem 2 is selected, and the system configuration for the third vertex point is

Option 2 for subsystem 1,
Option 1 for subsystem 2,
Option 1 for subsystem 3,
Baseline for subsystem 4,
Baseline for subsystem 5 .

The MCSP and cost of the third vertex point are

$$P_{c3} = P_{c2}\left(\frac{P_2^{(1)}}{P_2^{(o)}}\right) = .34\left(\frac{.85}{.75}\right) = .39 \quad \text{(IV-65a)}$$

and

$$C_3 = C_2 + \left(C_2^{(1)} - C_2^{(o)}\right) = 200.25 + (3.00 - 2.50) = \$200.75 \quad . \text{(IV-65b)}$$

The new weight for subsystem 2 for determining the fourth vertex point is

$$\lambda_2(4) = \lambda_{22} = \left(\frac{.97}{.85}\right)^{\frac{1}{1.50}} = 1.0920 \quad . \quad \text{(IV-66)}$$

The values $\lambda_1(4)$, $\lambda_3(4)$, $\lambda_4(4)$, $\lambda_5(4)$ are the same as the corresponding values of the set (IV-64).

The process for determining the remaining vertex points is repeated step-by-step, and the results of the calculations are listed in Table 15 where the system configuration for each vertex point is identified. The DSPC curve is displayed in Figure 10.

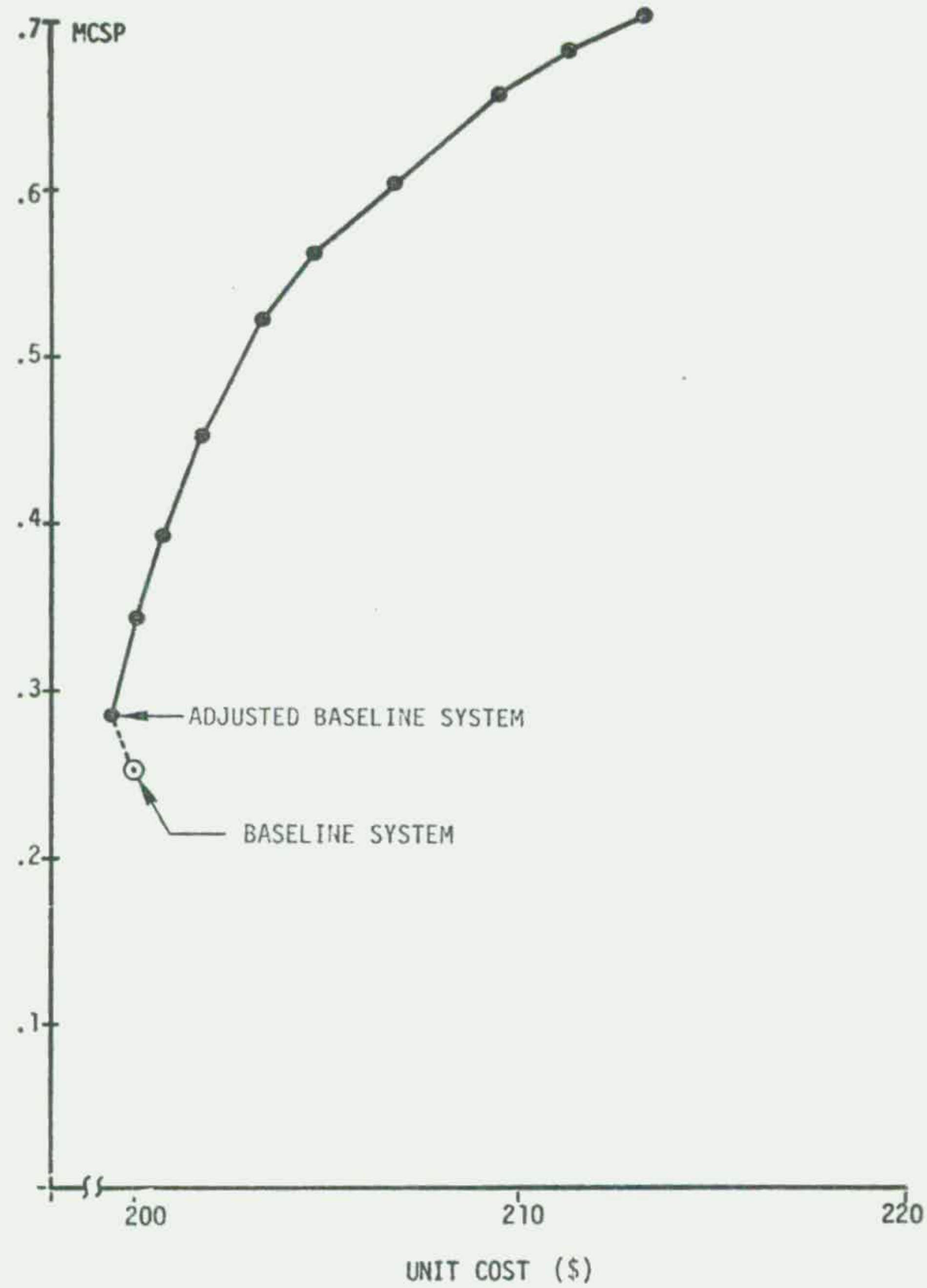


Figure 10. DSPC Results for Hypothetical Mine

Table 15

OPTIMAL CONFIGURATIONS FOR MINE EXAMPLE

VERTEX POINT	MINE CONFIGURATION (COMB. OF OPTIONS)					MCSP	UNIT COST ($)
	FIN	BRAKE	CUTTER	BODY	SAFE & ARM		
1	0	0	1	0	0	.28	199.50
2	2	0	1	0	0	.34	200.25
3	2	1	1	0	0	.39	200.75
4	3	1	1	0	0	.45	201.75
5	3	2	1	0	0	.52	203.25
6	3	2	1	0	1	.56	204.75
7	3	2	1	1	1	.60	206.75
8	3	2	2	1	1	.66	209.25
9	3	2	2	2	1	.68	211.25
10	3	2	2	2	2	.70	213.25

The subsystem options defined in Table 14 lead to 324 possible mine configurations, each with a certain MCSP and cost. Application of the DSPC algorithm determined that only 10 configurations are optimal. The remaining 314 configurations are nonoptimal and result in points below the DSPC curve.

A significant comment can be made on another aspect of the results shown in Table 15. Suppose, for example, that the Program Manager is required to purchase 100,000 mines at a unit cost of $200.00. This means that the total program cost is $20M. Since the number of mines and unit cost are specified, the Program Manager has essentially no flexibility in managing his program since only the first vertex point has a unit cost not exceeding $200.00. If, however, the only restriction on the Program Manager is to a fixed program cost of $20M, then the results of Table 15 can be utilized to negotiate with higher level decision makers to decide if it is more cost effective to invest more dollars early in the program to produce fewer but better mines at a higher unit cost. Suppose the program cost is $20M. The results shown in Table 15 can be translated into those of Table 16.

Table 16

DSPC RESULTS FOR A FIXED PROGRAM COST

VERTEX POINT	MCSP	UNIT COST ($)	NUMBERS PURCHASED	NUMBER OF OPERATIVE MINES EXPECTED	INCREASE OVER BASELINE
Baseline	.25	200.00	100,000	25,000	0
1	.28	199.50	100,250	28,070	3,070
2	.34	200.25	99,875	33,958	8,958
3	.39	200.75	99,626	38,854	13,854
4	.45	201.75	99,132	44,610	19,610
5	.52	203.25	98,401	51,169	26,169
6	.56	204.75	97,680	54,701	29,701
7	.60	206.75	96,735	58,041	33,041
8	.66	209.25	95,579	63,082	38,082
9	.68	211.25	94,675	64,379	39,379
10	.70	213.25	93,787	65,651	40,651

Table 16 shows that by purchasing fewer mines to maintain the $20M fixed budget, the number of expected operative mines increases significantly over the Baseline and Adjusted Baseline System values. The purchase of fewer mines may also result in savings due to less storage, delivery costs, etc. This example clearly illustrates the types of decision-making information that can be generated by the DSPC methodology.

In Section V-C, this mine example will be continued and extended to include system effectiveness when warhead options are considered.

F. THE RIGID "DESIGN TO UNIT COST" PROBLEM

To this point the handbook has presented techniques which the Program Manager could use to optimize system performance at various levels of cost. In the examples presented previously, subsystem options were obtained for the most critical subsystems, and the DSPC procedure was applied to determine optimal system configurations at different levels of cost. This led to increased system performance at increased cost. However, the chief concern within the military community is the unit cost limit imposed on a given weapon system; and until total production numbers, operational deployment tactics and some measure of effectiveness are defined the main concern is cost. The overwhelming reaction of project engineers has been that tradeoff techniques are invaluable in re-orienting cost goals; but, until changed, the unit cost is the governing factor in day-to-day system development.

In the introduction to this handbook, it was stated that the Program Manager should have a means to "identify subsystems whose performance levels are more than adequate to meet mission requirements and investigate if these subsystems can be replaced by lower cost subsystems (which generally implies lower performance) with the cost savings invested more effectively in the improvement of other more critical subsystems ...." The procedure for accomplishing this can best be described by extending the mine example discussed previously. The same procedure is applicable to any other system, and in many cases will lead to a high payoff in reducing system cost. In fact, this approach (resource allocation) might be the only way to meet mission requirements while staying within the constraints of DTC goals.

In the mine example, the MCSP model was applied first to determine the Baseline MCSP and also to provide the ranking of the subsystems in terms of their likelihood of experiencing a critical failure. The subsystem criticality ranking is presented in Table 2, page 34. The top five critical subsystems listed in Table 2 were then selected for reliability improvement considerations which led to the improved performance options listed in Table 14, page 79. Application of the DSPC methodology to these options for the top five critical subsystems then led to the optimal DSPC curve displayed in Figure 10, page 85.

It appears natural to seek improved reliability options for the more critical subsystems (at the top of the list in Table 2), since the emphasis is invariably on system improvement. However, the subsystems at the bottom of the list also should be investigated to determine if cheaper (which generally entails lower performance) options are available. This seems paradoxical to seek lower performance subsystems options at a lower cost. However, cost is an extremely important factor in system development, and the cost savings for less critical subsystems at the bottom of the list may be more effectively invested in improving the more critical subsystems at the top of the list. This often can lead to high payoffs. Of course, there may be certain subsystems which require high performance, more expensive options for some reasons such as safety or logistics considerations; and consequently, lower performance is not acceptable for such subsystems.

Suppose a cheaper, lower performance option is obtained for five of the less critical mine subsystems at the lower part of the list in Table 2. These cheaper options and the original baseline values are identified in Table 17.

Table 17

IDENTIFICATION OF CHEAPER, LOWER PERFORMANCE OPTIONS

SUBSYSTEM	ORIGINAL BASELINE			CHEAPER OPTION		
	MTBF (Hrs)	PERFORMANCE	UNIT COST	MTBF (Hrs)	PERFORMANCE	UNIT COST
Battery	2,500	.91	2.00	1,500	.85	1.25
Processor	2,500	.91	2.00	1,500	.85	1.25
Sensor A	5,000	.98	4.50	3,000	.96	1.50
Sensor B	3,000	.96	4.00	2,000	.94	2.00
Structure & Harness	35,000	.99	2.50	10,000	.98	1.00

The first step is to reestablish the Baseline System using the cheaper options identified in Table 17, and consider the original baseline subsystems as reliability improvement options. Combining these options with those already established for the more critical subsystems (Table 14, page 79) leads to the new set of subsystem options identified in Table 18. This new set of options leads to 10,368 possible mine configurations! Clearly, it would be a formidable task to investigate every configuration. This shows the necessity of the single DSPC optimization algorithm.

Table 18

NEW BASELINE SYSTEM AND SET OF SUBSYSTEM OPTIONS FOR MINE

SUBSYSTEM	BASELINE		OPTION 1		OPTION 2		OPTION 3	
	$P_i^{(o)}$	$C_i^{(o)}$	$P_i^{(1)}$	$C_i^{(1)}$	$P_i^{(2)}$	$C_i^{(2)}$	$P_i^{(3)}$	$C_i^{(3)}$
1. Fin	.70	1.00	.75	1.50	.85	1.75	.99	2.75
2. Brake	.75	2.50	.85	3.00	.97	4.50	---	----
3. Cutter	.80	3.00	.90	2.50	.98	5.00	---	----
4. Body	.88	5.00	.95	7.00	.99	9.00	---	----
5. Safe & Arm	.90	4.00	.97	5.50	.99	7.50	---	----
6. Battery	.85	1.25	.91	2.00	---	----	---	----
7. Processor	.85	1.25	.91	2.00	---	----	---	----
8. Sensor A	.96	1.50	.98	4.50	---	----	---	----
9. Sensor B	.94	2.00	.96	4.00	---	----	---	----
10. Structure & Harness	.98	1.00	.99	2.50	---	----	---	----

Since subsystems 6, 7, 8, 9, and 10 have new baseline values, the MCSP and cost of the new Baseline System becomes (using equations similar to (IV-7) and (IV-8))

$$P_o = .25\left(\frac{.85}{.91}\right)\left(\frac{.85}{.91}\right)\left(\frac{.96}{.98}\right)\left(\frac{.94}{.96}\right)\left(\frac{.98}{.99}\right) = .21 \qquad \text{(IV-67a)}$$

$$C_o = 200 - (.75 + .75 + 3.00 + 2.00 + 1.50) = \$192.00 \quad . \qquad \text{(IV-67b)}$$

Application of the DSPC methodology to the options in Table 18 leads to 15 optimal system configurations. There are 10,353 nonoptimal configurations! The optimal configurations are identified in Table 19. Examination of the system configurations for the first four vertex points in Table 19, shows that the money saved by substituting the cheaper, lower performance options may be allocated to improve the more critical subsystems. Furthermore, Option 1 (original baseline) for the Battery and Processor was not selected until the fifth and sixth vertex points, respectively, at a system unit cost below the $200 for the original Baseline System.

Table 19

OPTIMAL CONFIGURATIONS FOR MINE EXAMPLE WHEN RESOURCES ARE ALLOCATED OPTIMALLY

VERTEX POINT	MINE CONFIGURATION (COMBINATION OF OPTIONS)										MCSP	UNIT COST ($)
	FIN	BRAKE	CUTTER	BODY	SAFE & ARM	BATTERY	PROCESSOR	SENSOR A	SENSOR B	STRUCTURE & HARNESS		
1	0	0	1	0	0	0	0	0	0	0	.24	191.50
2	2	0	1	0	0	0	0	0	0	0	.29	192.25
3	2	1	1	0	0	0	0	0	0	0	.33	192.75
4	3	1	1	0	0	0	0	0	0	0	.38	193.75
5	3	1	1	0	0	1	0	0	0	0	.41	194.50
6	3	1	1	0	0	1	1	0	0	0	.43	195.25
7	3	2	1	0	0	1	1	0	0	0	.50	196.75
8	3	2	1	0	1	1	1	0	0	0	.53	198.25
9	3	2	1	1	1	1	1	0	0	0	.58	200.25
10	3	2	2	1	1	1	1	0	0	0	.63	202.75
11	3	2	2	2	1	1	1	0	0	0	.65	204.75
12	3	2	2	2	1	1	1	0	1	0	.67	208.75
13	3	2	2	2	2	1	1	0	1	0	.68	208.75
14	3	2	2	2	2	1	1	1	1	0	.69	211.75
15	3	2	2	2	2	1	1	1	1	1	.70	213.25

The DSPC curve for this example is displayed in Figure 11. For comparison purposes, the DSPC curve for the previous case (Figure 10) where only performance improvement options for top five critical subsystems were considered is shown as a dashed curve in Figure 11. Observe that at a unit cost of $200, the optimal allocation of resources yields an MCSP about 68% higher. Conversely, the achievement of a prescribed MCSP is obtainable at a lower cost.

Obtaining cheaper options for the less critical subsystems (and having options for the more critical subsystems) almost always leads to better results. If the original Baseline System is optimal, then the DSPC methodology will first select those cheaper options. This means that the Optimal Allocation curve will meet the original DSPC curve at the original baseline vertex point and then coincide with the original DSPC curve. Whenever the original Baseline System is nonoptimal the procedure will always lead to better results.

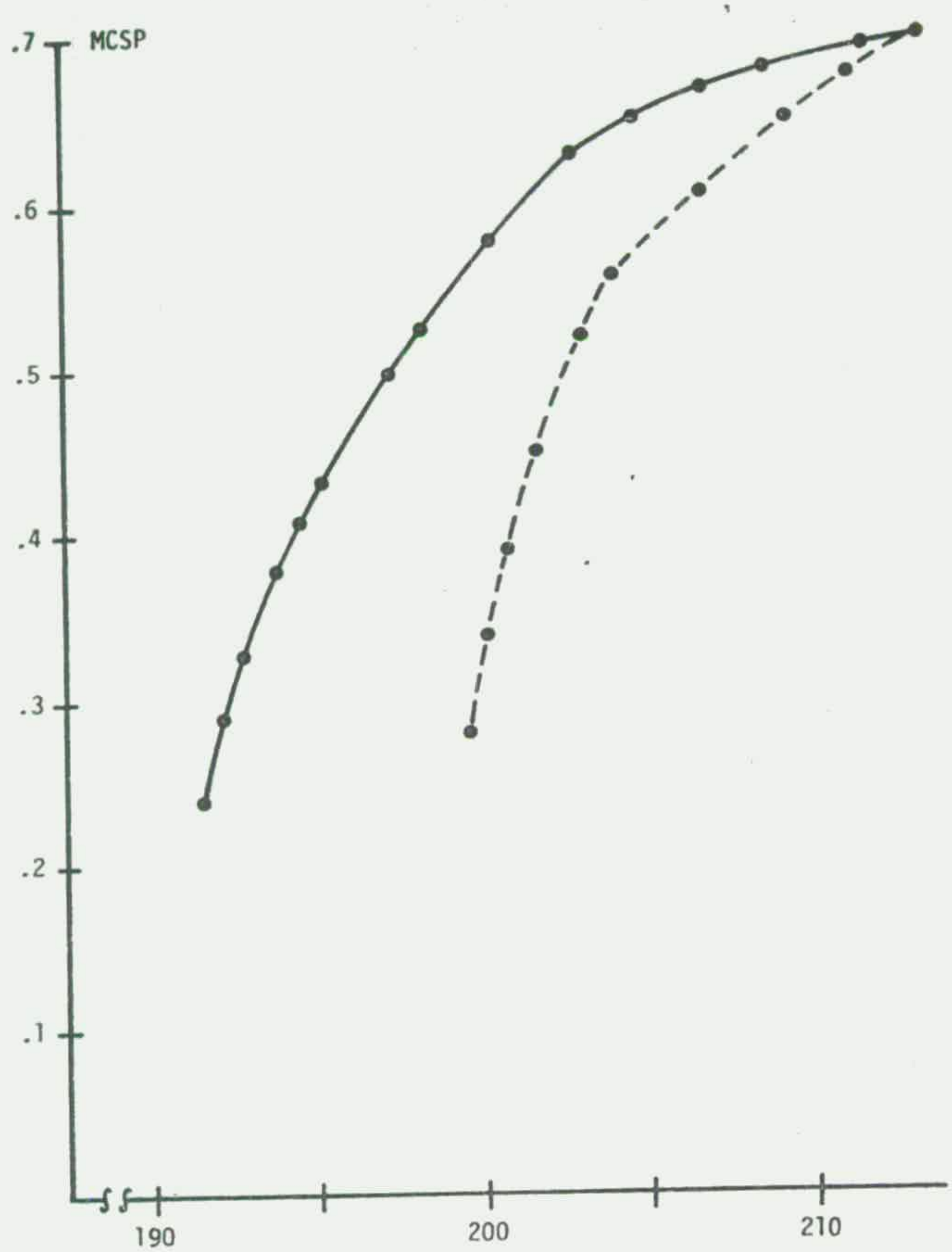


Figure 11. DSPC Results for Mine Example When Resources are Allocated Optimally

G. CONCLUSION

This section has presented a general description of the DSPC methodology together with examples to illustrate the simplicity of its application. The DSPC methodology, applied to a system under development, can be exercised continuously by a program engineer throughout the program to determine optimal system configurations at various cost levels. This provides the Program Manager with a tool for making day-by-day decisions and assessment of system progress based upon the best information available. It also provides valuable guidance to the Program Manager in meeting system DTC goals as well as a means for negotiating with higher decision makers in reestablishing performance or cost goals.

The next section extends this methodology to include a procedure for selecting the combination of subsystem options yielding the maximum system effectiveness at any prescribed cost.

SECTION V

DESIGNING TO SYSTEM PERFORMANCE/COST/EFFECTIVENESS METHODOLOGY

A. GENERAL

One very challenging task of the analyst is to develop an appropriate measure of effectiveness for a system which realistically and quantitatively measures the extent to which the system satisfies its specified objectives. Perhaps even more challenging is the development of a simplified measure of effectiveness which is meaningful and of value to both the analyst and the project engineer. A complex measure of system effectiveness (e.g., one requiring a large simulation model) may be important to the higher Decision Maker in determining if the system is sufficiently cost effective to warrant further development. However, the Program Manager is interested in developing the best system possible under given cost constraints, and a more simplified measure is usually desired which can be used on a day-by-day basis in the development of his system. Unfortunately, the effectiveness analyses of a developing system is usually accomplished outside the program office resulting in time delays and leaving the project engineer with little except intuition or past experience to weigh potential effectiveness improvement options. The analyst can provide an invaluable service by devising a measure of effectiveness which the program office can utilize on a continuous basis in the application of the DSPCE methodology. A few examples of measures of effectiveness of various systems are: sorties on target, targets destroyed, and cargo delivered. Numerous other examples could be cited. It is the intent of this section to show how a project engineer can optimize the effectiveness of his system once the analyst has determined an appropriate measure of effectiveness for use by the program office. In this section, it is assumed that the analyst has provided the project engineer with an appropriate measure of effectiveness for the system. When such a measure has been established and subsystem options directly affecting this measure of effectiveness become available, the Designing to System Performance/Cost/Effectiveness (DSPCE) methodology can be implemented. This methodology determines the combination of subsystem options (both reliability and effectiveness options) yielding the maximum system effectiveness at any prescribed cost. In this section, the DSPCE methodology is described, and the target activated munitions example considered in the previous sections is extended to illustrate the application of the methodology when effectiveness options are available.

B. IMPLEMENTATION OF THE DSPCE METHODOLOGY

1. No Effectiveness Options. For many systems, there are subsystem reliability options which affect the MCSP, but no subsystem options directly related to effectiveness. Certainly, the MCSP of the system plays an important role in the effectiveness of the system. Furthermore, improvements in MCSP result in quantifiable improvements in effectiveness. If, for example, certain avionics subsystems of an aircraft or the warhead of a weapon have been previously specified, the Program Manager has no freedom to change these subsystems (other than reliability improvement). In such a case, only the DSPC model is applicable; however, the resulting MCSP improvements are translatable into effectiveness improvements. Thus, the DSPC curve such as that illustrated in Figure 2 on page 15 is directly transformed into an optimal effectiveness curve with effectiveness improvements resulting solely from optimal subsystem reliability improvement options.

2. Effectiveness Options. When options exist for certain subsystems which have a direct influence (other than in the MCSP sense) on system effectiveness, then the DSPCE methodology is applicable. The general procedure for implementing the DSPCE methodology is described below and will be applied to a specific example in Section V-C.

Consider a hypothetical system for which only one subsystem directly affects the measure of effectiveness. Assume there are three options for this subsystem, each of which influences the system effectiveness to a different degree. Combined with the other subsystems, these can be considered as three separate systems denoted by S_1, S_2, S_3. Suppose the three systems are characterized as follows:

a. System S_1 is relatively simple and low cost with effectiveness E_1 provided S_1 does not experience a critical failure, i.e., maximum effectiveness is E_1.

b. System S_2 is more complex and expensive than S_1 but with $E_2 > E_1$ (providing S_2 does not experience a critical failure).

c. System S_3 is of high complexity and the most expensive option; however, its effectiveness E_3 is the highest (provided S_3 does not experience a critical failure).

The procedure for implementing the DSPCE methodology is to consider the systems separately and first apply the DSPC model to each system. In Figure 12a. typical DSPC results are shown for the three systems. Comparison of the first vertex point for each system shows that, proceeding from System S_1 to System S_3, the cost becomes higher and the MCSP becomes lower (because of increasing complexity). However, when the DSPC results for each system are transformed into effectiveness versus cost curves, results such as those shown in Figure 12b could be obtained. These results show that for cost between C_0 and C_1 subsystem reliability options should be selected from System S_1, i.e., one of the first 4 vertex points of S_1. For cost between C_1 and C_2, there are two optimal configurations for System S_2. For cost greater than C_2, System S_3 should be selected. The optimal effectiveness versus cost curve is depicted by the vertex points on the solid curve in Figure 12b. The dashed sections of the curves are nonoptimal but show the effectiveness if the Program Manager were restricted to use only one of the Systems S_1, S_2, or S_3.

The information displayed in Figure 12b shows the decision-maker which system (and combination of subsystem options for that system) provides the maximum effectiveness at any prescribed level of cost. Conversely, to achieve a prescribed level of effectiveness, the DSPCE methodology defines the system, the system configuration, and the associated cost to achieve that effectiveness.

C. DSPCE APPLIED TO TARGET ACTIVATED MUNITIONS

The DSPCE methodology will be applied to the hypothetical mine which was considered in the previous sections. Suppose there are three warhead options which directly influence system effectiveness. These three warhead options are listed in Table 20.

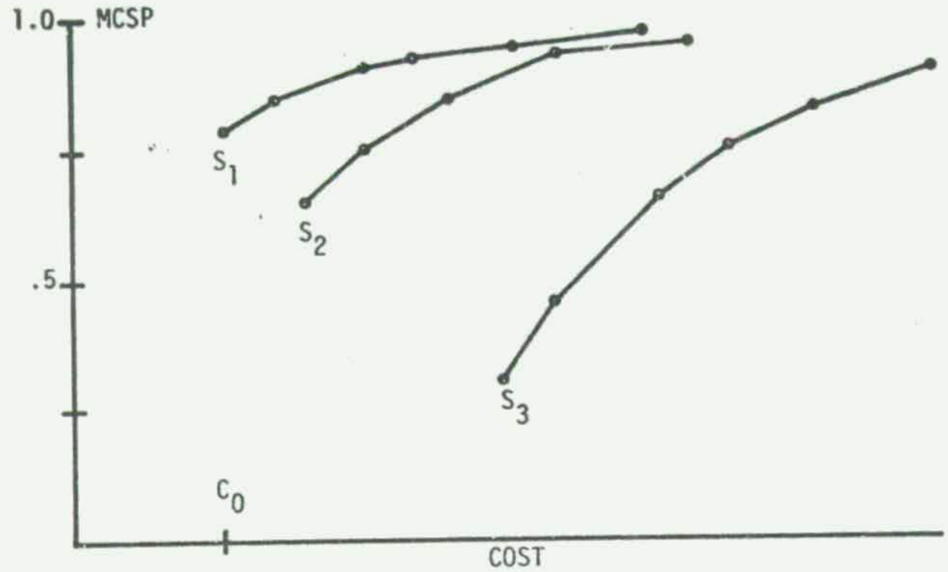


Figure 12a. MCSP of Systems S_1, S_2, S_3

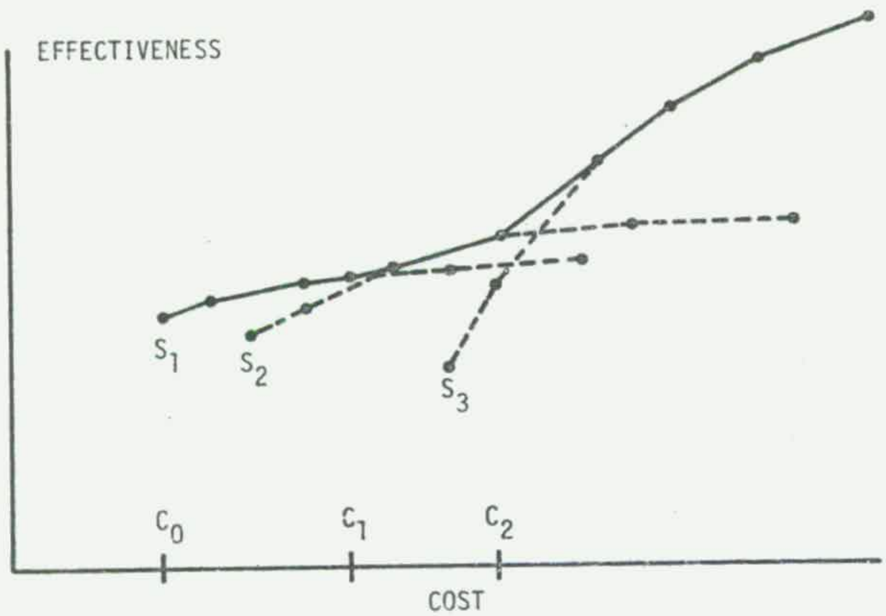


Figure 12b. DSPCE Results for Systems S_1, S_2, S_3

Figure 12. Illustration of DSPCE Methodology.

Table 20

WARHEAD OPTIONS

WARHEAD OPTION	KILL PROBABILITY OF WARHEAD P_k	COST ($)
1	.4	8.00
2	.6	12.00
3	.9	18.00

The kill probabilities in the table are conditional probabilities, i.e., the probability of killing the target given that the target is within range and the mine is operative. These 3 warhead options together with the subsystem options listed in Table 14 on page 79 lead to 972 possible mine configurations, each with a certain effectiveness and cost. The measure of effectiveness to be used is the probability that a single mine is operative and its warhead destroys a target that comes within range, i.e., MCSP x P_k. This measure is the everyday language of the project engineer and allows him to apply the DSPCE methodology on a daily basis. This measure also plays an important role in any more detailed effectiveness analyses dealing with such additional considerations as delivery modes, mine field density, tactics, etc.

Let System S_1 consist of Warhead 1 together with the remaining mine subsystems listed in Table 1, page 33, with subsystem reliability options defined in Table 14, page 79. Let System S_2 be defined similarly with the exception that Warhead 2 is used, and for System S_3 Warhead 3 is used. If the warhead is fixed, then system effectiveness improvements can only come from reliability improvements of the subsystems. The subsystem reliability options are defined in Table 14. From these options, the DSPC results listed in Table 15 were derived which defines 10 optimal vertex points of the MCSP versus cost curve. For a fixed P_k, the optimal effectiveness (MCSP x P_k) versus cost curve is obtained by multiplying the MCSP at each vertex point of Table 15 by P_k and adding the cost of the warhead under consideration. Applying this procedure with Systems S_1, S_2, and S_3 defined above yields the effectiveness results listed in Table 21 for the three warhead options.

Table 21

OPTIMAL EFFECTIVENESS FOR THREE WARHEAD OPTIONS

VERTEX POINT	SYSTEM 1 (Warhead 1)		SYSTEM 2 (Warhead 2)		SYSTEM 3 (Warhead 3)	
	MCSP × P_k	UNIT COST	MCSP × P_k	UNIT COST	MCSP × P_k	UNIT COST
1	.11	207.50	.17	211.50	.25	217.50
2	.14	208.25	.20	212.25	.31	218.25
3	.16	208.75	.23	212.75	.35	218.75
4	.18	209.75	.27	213.75	.41	219.75
5	.21	211.25	.31	215.25	.47	221.25
6	.22	212.75	.34	216.75	.50	222.75
7	.24	214.75	.36	218.75	.54	224.75
8	.26	217.25	.40	221.25	.59	227.25
9	.27	219.25	.41	223.25	.61	229.25
10	.28	221.25	.42	225.25	.63	231.25

The table shows, for instance, that vertex point 3 for System 2 yields a higher effectiveness at the same cost as vertex point 6 for System 1. The results of Table 21 are plotted in Figure 13 which clearly show which warhead is preferred at various levels of cost. The optimal effectiveness versus cost curve is depicted by the vertex points on the solid curve. The dashed sections are nonoptimal but show the effectiveness if the Program Manager were restricted to use only one of the three warheads. The optimal combination of subsystem options corresponding to each vertex point in Figure 13 is defined in Table 22. Of the 972 possible mine configurations, 955 are nonoptimal, i.e., yield points below the DSPCE curve.

The results in Table 22 can be used to show the consequences, in terms of effectiveness, of purchasing fewer more effective mines while maintaining a fixed program cost of $20M. The discussion would be analogous to that of Table 16 on page 77.

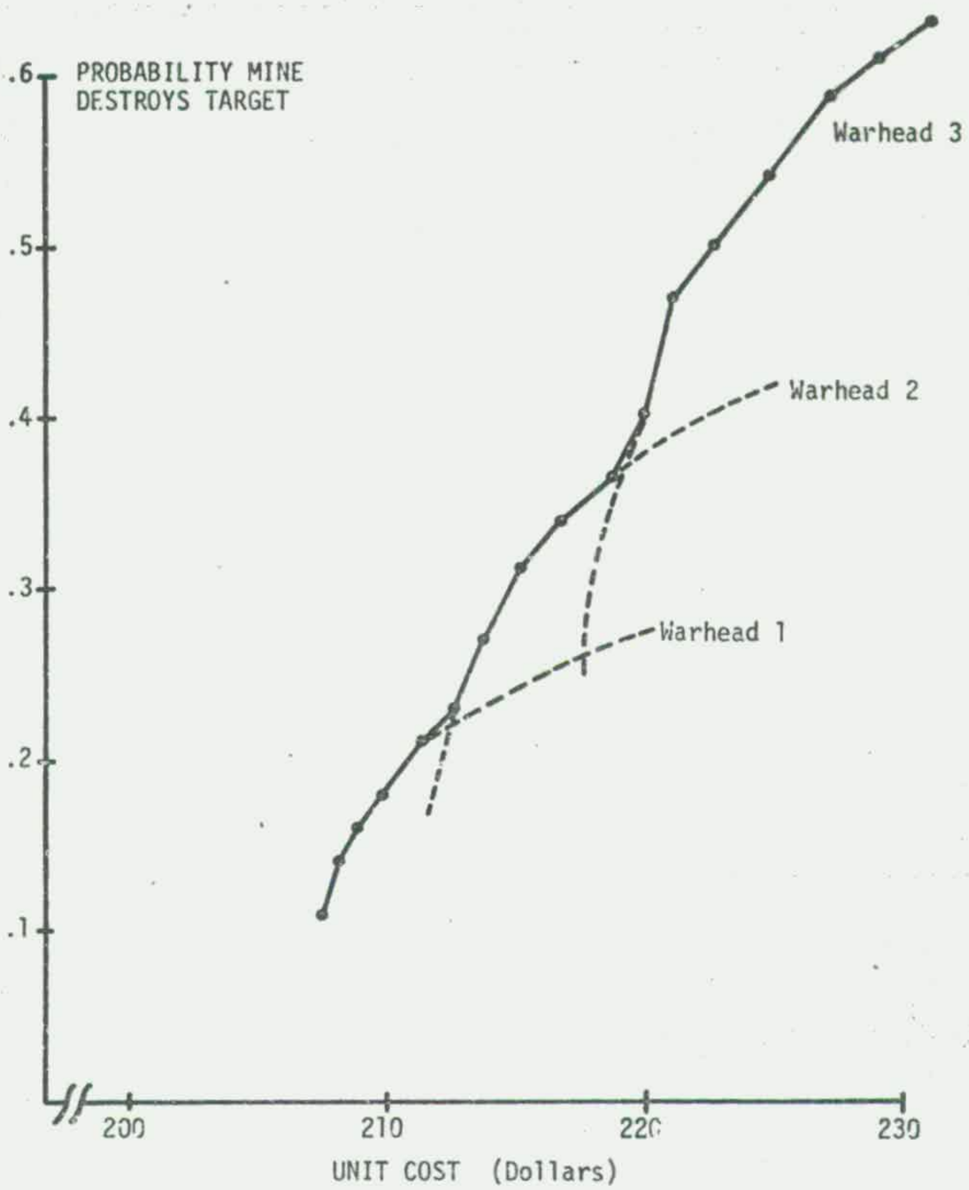


Figure 13. DSPCE Results for Hypothetical Mine System.

Table 22

OPTIMAL DSPCE CONFIGURATIONS FOR MINE EXAMPLE

VERTEX POINT	CONFIGURATION (SUBSYSTEM OPTIONS)						PROBABILITY MINE DESTROYS TARGET	UNIT COST
	FIN	BRAKE	CUTTER	BODY	SAFE & ARM	WARHEAD		
1	0	0	1	0	0	1	.11	207.50
2	2	0	1	0	0	1	.14	208.25
3	2	1	1	0	0	1	.16	208.75
4	3	1	1	0	0	1	.18	209.75
5	3	2	1	0	0	1	.21	211.25
6	2	1	1	0	0	2	.23	212.75
7	3	1	1	0	0	2	.27	213.75
8	3	2	1	0	0	2	.31	215.25
9	3	2	1	0	1	2	.34	216.75
10	3	2	1	1	1	2	.36	218.75
11	3	1	1	0	0	3	.41	219.75
12	3	2	1	0	0	3	.47	221.25
13	3	2	1	0	1	3	.50	222.75
14	3	2	1	1	1	3	.54	224.75
15	3	2	2	1	1	3	.59	227.25
16	3	2	2	2	1	3	.61	229.25
17	3	2	2	2	2	3	.63	231.25

D. CONCLUSION

This section has presented the development of the DSPCE methodology along with an example of the application of the methodology. The DSPCE methodology analyzes effectiveness as well as reliability to identify the combination of subsystem options yielding the maximum effectiveness at any prescribed cost.

In the next section, the management tools developed in the previous sections are summarized, and data requirements and availability for implementing the models are briefly discussed.

SECTION VI

SUMMARY

This handbook has presented methodologies designed to provide a Program Manager with analytic tools for solving a multitude of problems encountered in the course of system development. Briefly stated, these management tools allow for continuous and systematic:

- Evaluation of overall system reliability (MCSP).

The MCSP model determines the probability that a system completes its mission without being degraded below acceptable limits because of a critical failure of one or more of its subsystems. MCSP models can also be used to identify the critical subsystems and show the overall system MCSP enhancement due to reliability improvement of one or more critical subsystems.

- Optimal allocation of resources in system reliability improvement Programs (DSPC).

The DSPC model can be employed during the conceptual phase or very early in the development phase to select the initial or Baseline System Configuration from among competing subsystems, or it can be applied later in the development process if a reliability improvement program is undertaken.

- Optimal allocation of resources in system effectiveness improvement programs (DSPCE).

When options in the form of varying levels of effectiveness and the cost associated with each level are available, the DSPC methodology can be implemented to determine that combination of subsystem options yielding the maximum system effectiveness at any prescribed cost. However, it goes without saying that the decision-making information provided by these methodologies can only be as good as the data that is input. Therefore, the importance of a valid data base cannot be over emphasized. If for certain programs the data base is not available, or if the quality of the data is suspect, steps should be taken immediately to establish the necessary data base, or make the necessary improvements. This is particularly true for applications of the methodologies during the conceptual and definition phases of system development. Once testing begins, the necessary data can be collected in conjunction with the test program. The type of data required to implement the various models is clearly illustrated in the various examples presented in this handbook. Thus, anyone desiring to utilize the methodology can readily see the exact nature of the data required and take the necessary steps to acquire this data. The methodologies presented in this handbook allow the Program Manager to evaluate his system and make optimal decisions based upon a constantly improving data base. Without the required data, decisions can only be based upon intuition or past experience.

Reference 7 contains a tabulation of various data sources which could provide valid inputs for a wide range of applications of the methodology presented in this handbook. Reference 8 contains a similar tabulation.

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